Committee I
The Nuclear Option in the Past,
Present and in the Future

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THE LESSON OF CHERNOBYL

by

Geroge Marx
Department of Atomic Physics
Eotvos University
Budapest, HUNGARY

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George Marx
Department of Atomic Physics, Eötvös University
Budapest H-1088

Fuel, Moderator, Coolant

Uranium is made of two isotopes. One of them, ^{238}U has a half life comparable to the age of Earth (4.5 billion years). The other one, ^{235}U has a half life much shorter (0.7 billion years), it makes today only 0.7% of natural uranium.

When uranium is irradiated by slow neutrons, the released binding energy of the captured neutron is not enough to cover the activation energy for fission in ^{238}U, but it is enough to split the ^{235}U. In the fission of ^{235}U 2-3 neutrons are released, this makes the nuclear chain reaction possible.

The neutrons emitted in fission are fast. They slow down gradually by elastic collisions, if they are not captured. Unfortunately, ^{238}U captures the medium-energy neutrons without fission, so in natural mix of uranium isotopes the fission neutrons are absorbed by ^{238}U before degrading to thermal energies, where they would be able to induce fission again in ^{235}U with good efficiency. In pure natural uranium the chain reaction is impossible.

The solution of the task is the inhomogeneous nuclear reactor. The uranium fuel rods are arranged as a lattice of rods, surrounded by materials in which the neutrons suffer elastic collisions. If the diameter of uranium rods is smaller than the mean free path of neutrons, the neutrons produced in fission leave the uranium rod, suffer collisions in the *moderator*, they slow down to the energies of the thermal motion. Then by random walk the thermal neutrons get back into a uranium rod. For slow neutrons the capture probability of ^{238}U is already low, but the fission probability of ^{235}U is high, thus they can produce further fissions, the chain reaction may run further (figure 1). It is evident, that the nuclei of the moderator material have to fulfill two conditions:

A. They must be light nuclei, in elastic collisions these take over a considerable fraction of the kinetic energy of the neutron
B. They must have low absorbtion probability for neutrons in the whole energy range.

E.g. light hydrogen (H) ideally fulfills Condition A, but poorly satisfies Condition B, because H may capture neutrons to make heavy hydrogen (D). The He and O nuclei excellently fulfill condition B: being close-shell structures, they practically don't absorb neutrons. The D and C nuclei offer a good compromise: they are relatively light and they absorb neutrons weakly. Therefore He gas, graphite (C), heavy water (D_2O) are good moderators. Common light water (H_2O) is poorer moderator, due to the $n + \mathrm{H} \rightarrow \mathrm{D}$ absorbtion. Natural uranium plus light water moderator cannot realize a self-sustaining chain reaction, but they almost can: the neutron-multiplication factor of this system can reach 0.98. If, however, the uranium is enriched in ^{235}U a bit (from the original 0.7% to 2-3%), the enriched uranium fuel plus light water moderator system may sustaining a fission chain.

The heat produced by the fission chain must be removed by a flow of *coolant*, in order to cool the reactor and to transfer the heat to the turbines for utilization. Possible coolants are He, D_2O, H_2O, liquid Na. One has to make a compromise between nuclear properties, technological advantages and economic considerations. E.g. He and D_2O are good coolants from nuclear point of view, but helium performs poorly technically (as a gas, it has low density and low heat capacity). D_2O is expensive. Now 90% of the reactors use *enriched uranium* as fuel, *light water* as moderator, *light water* as coolant, in spite of the fact that H_2O is a weak reactor poison: it eats a fraction of the neutrons.

Void coefficient

Let us consider a fixed amount of fuel and add a small amount of moderator. The moderator is not enough to slow down the neutrons to thermal energies; the neutrons may reach a uranium rod at medium energies, so they are consumed by ^{238}U uselessly. If we increase the *moderator/fuel* ratio, more and more neutrons are thermalized before entering a uranium rod, larger and larger fraction of neutrons induce new fissions: the neutron multiplication increases.

At a certain moderator/fuel ratio we reach the point where practically all the fission neutrons have already become moderated to thermal energies before reaching an uranium rod again. At this moderator/fuel ratio the neutron multiplication has a maximum. It is of no use to increase the amount of moderator any further: the neutrons are anyway thermalized, they will not become slower in further collisions, but a longer random walk in the moderator increases their chance of being absorbed before entering the next uranium rod (figure 2). If the increase of the moderator/fuel ratio makes the multiplication factor larger the reactor is called *undermoderated.* If the increase of the moderator/fuel ratio decreases the neutron multiplication, the reactor is called *overmoderated.*

Let us consider e.g. a uranium-fueled, water-moderated, water-cooled reactor. Let us imagine that the reactor becomes overheated by chance. The cooling water boils, bubbles are created in the pipeline. The amount of water (which is coolant moderator and weak reactor poison at the same time) decreases. If the reactor is critical (multiplication factor = 1) and undermoderated, removal of water (moderater drop) decreases the multiplication factor below 1, thus the reactor stops automatically. Formation of voids decreases the neutron multiplication! We say that *an undermoderated reactor has a negative void coefficient, it is structurally stable: loss of moderator and coolant decreases the multiplication factor, it kills the chain reaction.* (The void coefficient is the derivative of the multiplication factor with respect to the moderator volume.)

Let us consider a uranium-graphite-water reactor (figure 1), which is overmoderated (having a high graphite/uranium ratio too high). If the reactor is critical (multiplication = 1), and due to statistical fluctuation or disturbance it becomes overheated, then the cooling water starts boiling, voids are created. Removal of water means not only less moderator, but less reactor-poison: Formation of voids enhances the neutron multiplication, the chain reaction is about running away (figure 1). *An overmoderated reactor has a positive void coefficient, therefore it is structurally unstable: loss of moderator and coolant increases the multiplication factor, it accelerates the chain reaction.*

Overmoderated reactors

Most of the operating power reactors operating at present work with enriched uranium as fuel, using light water for both: moderator and coolant. In case of sudden rise of the teperature, the water begins boiling. Bubble formation means partial removal of the moderator, thus the neutron chain reaction stops. These reactors are undermoderated by design, therefore they are structurally stable.

But this is not the whole story.

The first self-sustaining reactor (built by Fermi and Szilard in Chicago, having become critical at 2 December 1942) used natural uranium as fuel and graphite as moderator. It did not possess an extra cooling system, therefore it run at low power. (It was air-cooled.) It operated only for a short time, at first in the downtown Chicago, then in the Argonne Forest.

The first "professional" reactors were built later to utilize a fraction of neutrons for plutonium breeding:

$$n +^{238} U \to^{239} U \to {}^{239}Np \to {}^{239}Pu \qquad (*)$$

They had to work at high thermal power, to produce enough plutonium for nuclear weapons before the end of the war. (^{239}Pu can sustain nuclear chain reaction without moderator, therefore it is an appropriate material for the atomic bomb.) These reactors were designed by Eugene Wigner, they used natural uranium as fuel, graphite as moderator, water as coolant (figure 2). At that time it was a common belief, that uranium ore is scarce (the overall uranium supply of our planet was estimated to be 20000 tons), thus the intention was to work with as little uranium as possible. In these Hanford reactors there was a limited amount of uranium, with a huge amount of graphite added. The reactors were overmoderated, but actually they worked fine. They produced plutonium for the Trinity and Nagasaki bombs.

After the war, in 1948 the United States created a Reactor Safety Commission, headed by Edward Teller. Teller took the following position: if something has been invented, the industry will realize it. Only after the first accident the engineers begin bothering about the danger. But nuclear reactors are too dangerous to follow this pattern. The Nuclear Safety Commission started to think about the worst possible accident before it happened. In 1950 this commission discussed the structural dangers of overmoderated reactors. If these reactors become overheated, the water coolant boils away, thus reactor poisson is removed, the neutron chain reaction runs away. Teller proposed the decommissioning of the overmoderated Hanford reactors. The proposal was realized soon: the reactors were closed down. But these actions happened in the cold war era, there are no public discussions about it. In 1955 (at the era of Peaceful Atom Conference in Geneva, at the time when nuclear power stations started operating) this issue was made public, but in those years of optimism no one paid special attention to it.

The USSR began mass producing plutonium and constructing larger and larger power stations, several ones near to its Western borders, to cover not only the increasing electricity demand of the European part of USSR but also that of other Eastern European countries. One of the most economical constructions was the graphite-moderated channel reactor. This was built of separate moduls, each modul being a column 25cm·25cm thick and

3.5m high (figure 3). Each column contains wires of 1.8% enriched uranium in zirconium coating, graphite around it, and pipes for water cooling. The construction of the power reactor meant just putting these units side by side, and connecting the water pipes to the pumps. One could increase the power of the reactor by adding new columns (figure 3). The fissionable ^{239}Pu is produced from ^{238}U via reaction (*). If, however, the fuel elements are left in the reactor for several months, ^{239}Pu may capture a further neutron,

$$n +^{239} \mathrm{Pu} \longrightarrow^{240} \mathrm{Pu},$$

and ^{240}Pu (like ^{238}U) absorbs neutrons without fission, thus it acts as reactor poisson. For chemical ^{239}Pu extraction the fuel rods have to be removed from the reactor after a couple of weeks. – Well, in the channel reactor the exchange of fuel elements could be performed even during the operation of the reactor: it meant only disconnection and exchange of one column at a time.

100 km north of Kiev, in Chernobyl four such power reactors were built. One reactor consisted of 1693 columns, containing altogether 180 tons of enriched uranium and 2500 tons of graphite. In the pipes light water was circulated under 6.5 atm pressure. In this way the water was heated up to 280°C without boiling, increasing the thermal efficiency of the system near to 30%. The reactor produced 3.2 GW heat. (1GW = 10^9 watt). To remove this amount of heat, light water coolant transfers the heat to the heat exchanger, then in the two turbines each reactor generated 1GWatt electric power.

In a small lattice of columns a considerable fraction of neutrons escaped through the surface of the reactor. More and more columns were added, to improve the economy, thus the Chernobyl type reactors became overmoderated.

The structure instability of the reactor was compensated by additional safety systems, which were able to shut down the reactor, by pushing in neutron absorbing control rods automatically and by flooding it by neutron-absorbing, boron-rich water, in case of fast rising neutron multiplication or temperature.

April 1986

In such a reactor, producing 3.2 GW of heat, the intensive cooling is absolutely essential. Huge pumps, driven electrically, pushed 10000 liters of water (under the pressure of 6.5 atm, at the temperature 280°C) through the reactor in every second. – "But what happens in the case of an electric failure? There are Diesel engines certainy, as a substitute, but to rev them up to full rotation sped, they need about 1 minute! A time to long." – This question was raised by the enthusiastic young electric engineers and operators. They speculated about utilizing the rotational energy of the giant turbine wheels to generate electricity for bridgeing this time gap. A smart idea. They made real-life experiments already beforehand, but there was a last problem to be solved. As the wheels slowed down, the induced voltage dropped, the pumps failed to work smoothly. A rearrangement of the electric circuits may help. To make the last experiment, an opportunity was offered: After the peak winter power demand was over, a shut-down of Reactor 4 at the Chernobyl power station was planned for the morning of Friday 25 April 1986. The time-sequence of events is known from the reconstruction, made by the Soviet Atomic Energy Commission.:

25. April, 1.00 a.m. The reactor works at 3.2 GW thermal power. Decreasing of power begins.

13.05 p.m. The power is at 1.6 GW. One of the two turbines is turned off.

14.00 The emergency control cooling system (flooding with boronated water) is disconnected. (The operator intend to be at the wheel, unperturbed by any dull automatics.)

14.05 Unexpected power demand is indicated by the energy authorities. The reduction of power is interrupted. The reactor works at 1.6 GW thermal power, supplying electricity to the notional network.

23.10 The outside power demand drops. Permission is given to turn off the reactor. The reduction to 0.7 GW thermal power begins.

26. April, 0.28 a.m. The experiment may begin with 24 hours of delay, after an unintended tireing day. The local control has been turned off. The neutron flux is controlled only globally by the safety automatics. To be on the "safe side", the operator lets the water circulate with a speed exceeding the maximum permitted value. Due to the fast turnover, the water does not have time to cool, it is near the boiling point. The reactor shows signs of instability. Instead of reaching the intended 0.7 GW smoothly the power suddenly drops to 0.03 GW.

1.07 The reactor is stabilized at 0.2 GW thermal power. The circulation of the cooling water (being near the boiling point) was reduced.

1.22 The last computer printout indicates 0.2 GW thermal power. Several problems have accumulated, however. The reserve reactivity is only 50% of the permissible minimum value, that is the neutron-absorbing control rods are too high up (figure 5). This was forced by the fact that during the long operation at low power Xe poisoning has been built up. (Fission of ^{235}U produces considerable amount of ^{135}I, which decays to ^{135}Xe with a half life of 6-7 h. This Xe isotope - due to its deficient nuclear shell - absorbs neutron with an extreme high probability, it is a strong reactor poison. When the reactor works at high power, the many neutrons eliminate the ^{135}Xe by $n + ^{135}\text{Xe} \rightarrow ^{136}\text{Xe}$. When the reactor power drops, the ^{135}I isotops present produce ^{135}Xe by decay, but there are no neutrons enough to eliminate this ^{135}Xe, therefore the reactor poison accumulates. In this poisoned state a sudden increase of neutron number eliminates the poison, the neutron multiplication increases further. This positive feedback makes the reactor unstable against fluctuations.) – If the control rods are high up, the time needed to push them in (or fall down by free fall) 10 meters becomes longer than 1 second. In the state of instability (undermoderated and Xe-poisoned reactor with some of the automatic controls turned off) the reaction time of the reactor to the positive feedback is smaller than 1 s. In such a state the reactor manual forbids any action. As the Soviet investigator later said: "At this state of affairs not even the prime minister can allow to go on with the intended experiment"

1.23,04 seconds: Power is 0.2 GW. The experiment begins. The operator wanted to be the lord of the reactor, he switches the automatic scram off. The values leading to the second turbine are now turned off.

1.23,20 seconds: Due to the intervention of closing the values, the neutron multiplication increases. In such an emergency automatics would scram the reactor by dropping in the control rods, but this automatics has been turned off.

1.23,21 seconds: The control rods begin to move in, but too slowly. The lower part of the control rods was made of graphite, the upper part of neutron absorbing boron-steel alloy. As the graphite sector enters, expelling water, weak poisoning water is replaced by not absorbing graphite, what increases the neutron multiplication factor by a few procent (figure 5).

1.23,31 seconds: As a consequence of the increase of multiplication the neutron density begins growing locally very fast, but the local control had been turned off earlier.

1.23,40 seconds: The thermal power of the reactor increases to 0.32 GW in half a minute. The operator decides to press the AZ5 scram button, in order to drop the neutron absorbing control rods in.

1.23,43 seconds: The thermal power is at 1.4 GW and it doubles within every second. Locally the reactor becomes prompt critical. (Not only the total number of neutrons, but even the number of the prompt neutrons coming immediately from the fission processes is increasing. Any human or automatic action can catch only the delayed neutrons. A prompt critical state does not respond to any outside control.) The high power alarm sounds. The sudden temperature rise produces such an uneven thermal expansion, that the control rod channels get deformed and fracture. The control rods cannot get down.

1.23,45 seconds: 3 GW thermal power. Global runaway in the Reactor 4 on its both sides.

1.23,46 seconds: The cooling water boils away. With the departure of light water (which is a mild reactor poison), due to the positive void coefficient the neutron multiplication increases further.

1.23,47 seconds: due to the high temperature and thermal expansion, the uranium rods open up. (The nuclear chain reaction stops.)

1.23,48 seconds: the water pipe lines open up.

1.23,49 seconds, 45 seconds after the initiation of the experiment: the boiling water produces a thermal explosion. The core of the reactor opens up (figre 6).

1.24: Under normal conditions the graphite moderator, the cooling water and the zirconium coating of the fuel rods are spacially separated. Now they get into contact. Above 1000 or 1200 °C chemical reactions start:

$$\mathrm{C} + \mathrm{H_2O} \rightarrow \mathrm{CO} + \mathrm{H_2},$$

$$\mathrm{Zr} + 2\mathrm{H_2O} \rightarrow \mathrm{ZrO_2} + 2\mathrm{H_2}.$$

The flammable hidrogen and carbon-monoxide gases get mixed with the outside air, which results in a second (chemical) explosion:

$$2\mathrm{H_2} + \mathrm{O_2} \rightarrow 2\mathrm{H_2O},$$

$$2\mathrm{CO} + \mathrm{O_2} \rightarrow 2\mathrm{CO_2}.$$

The reactor was not enclosed in containment. The explosions destroy the roof. Radioactivity is released into the atmoshpere.

2 April - 5 May: The fire in the building is extinguished soon, but larger and larger fraction of the graphite catches fire within the open reactor. At the high temperature the volatile fission products (Xe, Kr, I) and the easily diffusing fission products (Cs, Te) diffuse out from the fuel rods into the graphite. As the graphite burns, they get to the atomosphere with the smoke. Finally, on 5 May the reactor is covered by sand led, the release of radioactivity practically stops (figure 8).

This is the brief history of the tragic nights. The operator and the electric engineer from outside, these young "heroes" of the tragedy who intended to increase the reactor safety by milking the energy of the turbine wheels, but they paid attention only to the electric variables "relevant" for the success of the experiment (and did not bother about other variables indication the dynamics of the chain reaction) died on the spot immediately, due to the explosion. Their names are Valery Hodiemchik and Vladimir Sashionok. 29 people died in the following weeks due to the irradiation suffered in and around the destroyed building of the Reactor 4, including those who were fighting the fire. And more people will die all around Europe due to delayed effects (leukemia, cancer) of the received low level doses.

The unit of activity is 1 Bq=1 Becquerel=1 radioactive decay/second. The release of radioactivity in the large scale contaminations of the history of the 20th century are estimated to be:

Hiroshima bomb	0.01 EBq
Modern hydrogen bomb	0.1-10 EBq
Windscale reactor accident (UK, 1957)	0.04 EBq
Three Mile Island accident (USA, 1980)	0.001 EBq
Chernobyl accident (USSR, 1986)	4 EBq

(Here 1 EBq=10^{18} Bq=10^{18} radioactive decays/s.) We see that the atmospheric contamination due to Chernobyl is roughly comparable to the cumulative contamination produced by the atmospheric bomb tests. The release of radioactivity happened in the week between 26. April and 4. May, with two peaks: 26. April (the explosions) and 4. May (peak of the graphite fire, just before being extinguished). (Figure 8.)

All the reactor accidents happen at down of weekends. 26 April was Saturday of the orthodox Eastern. Most of the responsible bosses were in their dachas. The main concern of the local authorities present was the cover-up, interpreting the accident as a fire in the building, extinguished within hours. This caused delays of days with the large scale alarm and evacuation.

Fortunately, on Saturday morning of 26 April the wind was blowing towards northwest, away from Kiev, carrying the radioactivity to uninhabited swamp area. The release reached Finland and Sweden, where the first alarms rang. Saturday evening the wind direction turned west, blowing the activity to Poland, Scandinavia, Scotland, Sunday the release of radioactivity decreased, that activity was scattered by the turning wind to Germany, Czechoslovakia, Austria, Italy. (From this release the rain on the holiday 1 May produced fall-out in North-Western Hungary.) But the release of radioactivity went on, at gradually increasing rate, due to the spreading of graphite fire through the whole next week. A week later the grace given to Kiev was over: the wind turned southwards. Unfortunately, the authorities of Kiev missed the opportunity: the evacuation of the children began only after the arrival of the contamination. With the southbound wind this second large release reached later Romania and Bulgaria. (It entered Hungary after a long detour from the south-east. The contamination in Hungary was moderate, figure 9, thanks to the lucky winds and to the northern shield of the Carpatian Mountains. The fallout was uneven, depending on the rainfall at the time of the atmospheric contamination. The worst contaminated area was Budapest (800 km from Chernobyl), not because of the wind and rain but because of the smog. The active contamination precipitated on to the aerosol floating above the city, and then with that it descended to the ground, producing a surface contamination about 50 000 Bq/m^3 in the city. (The average surface contamination in Hungary was 5000 Bq/m^2.) The air was cleared by the May and June rainfalls (and by the decay of volatiles), the situation slowly returned to normal values at thee end of the year. (The overall air contamination in Hungary after the Chernobyl accident was of the same order of magnitude as in the early 1960-es, at the peak of atmospheric bomb tests. Figure 7.)

The Years After

The escaped radioactive izotopes were those fission products, which diffused at fastest rate from the ruptured fuel rods into the burning graphite. (This caused a distribution different from nuclear bomb explosions, where all the radioactive izotopes get to the atmosphere.)

^{135}Xe	(100%)	$1680\cdot10^{15}$Bq	(9 hours)
^{85}Kr	(100%)	$35\cdot10^{15}$Bq	(10 years)
^{131}I	(20%)	$37\cdot10^{15}$Bq	(8 days)
^{132}Te	(15%)	$150\cdot10^{15}$Bq	(3 days)
^{134}Cs	(10%)	$18\cdot10^{15}$Bq	(2 years)
^{137}Cs	(13%)	$47\cdot10^{15}$Bq	(27 years)
^{90}Sr	(4%)	$8\cdot10^{15}$Bq	(28 years) etc.

The most important isotopes are the biologically active ones: the iodine (used by animals and humans to be incorporated in the thyroid), caesium (mistaken to potassium and incorporated in muscules), strontium (mistaken to calcium and incorporated in the bones). In case of atomospheric bomb tests the most harmful is the release of ^{90}Sr, which is incorporated in the bones (made of $CaPO_3$), near to the bone-marrow, where the red blood cells are produced, thus causing leukemia. Fortunately, due the slow diffusion of strontium, the ^{90}Sr release in Chernobyl was much smaller than expected. This was one of the proofs that the stuff of the fuel rods did not get fully to the atmosphere. (About 10% of the graphite burned.)

The short-range contamination from ^{131}I was more dangerous. In May the grass was growing fast, incorporating ^{131}I from the rainfall. The cattle was already grazing after the winter, they concentrated the iodine into the milk, to cover the increased iodine demand of the fast-growing calves. But the same milk was consumed by children, who accumulated the iodine (the active ^{131}I included) into their growing thyroid. The irradiation there may cause thyroid cancer in the coming years. (Indeed, in Budapest we measured milk activities up to 1000 Bq/liter, thyroid activities up to 600 Bq/person.) But is was possible to protect the population from this contamination by forbidding cattle grazing during

May, by destroying milk in the affected regions, and by suppressing milk consumption of children. The ^{131}I danger passed away for June due to the 8 days half life of this nucleus. (Thus in Hungary the ^{131}I contamination was under control.)

The long range contamination, being present now as biological hazard, is ^{137}Cs, which dropped to the soil and stays there for 27 years and more, subjected to geological dilution. This may get to the vegetables, mushroom, strawberry (growing fast after rain in the spring of 1986), and also to the grazing animals (reindeer, rabbit, sheep etc.) This is why the vegetable and meet trade, import, consumption was under strong control in the whole Europe. Consumption of reindeer meat in the North, that of mutton in the West were forbidden for a long period. (This created possibility for commercial tricks. For example Austria, Germany and Italy prohibited the import of vegetables and fruits from Hungary, laying to the East of them. It was pretty hard to convince the authorities of those countries that Hungary was less affected by fallout than they were. Our Department strongly participated in the control of the food radioactivity.)

The unit of the dose is 1 mSv=1 millisievert, which corresponds to a biological effect equivalent to the effect of gamma radiation, depositing 0.001 Joule of ionisation energy per body kilogram. This unit was and is used, to express the biological effects of the Chernobyl accident.

The average natural background irradiation of people is 2 mSv/year (of this, about 1 mSv comes from the inhaled radon, emitted by the uranium decay chain in the soil and building material). The average dose, due to medical X rays in Europe is about 0.7 mSv/year. (Tooth X ray test gives 0.2 mSv, chest X-ray test above 1 mSv, gut X-ray test even more.) The collected doses by nuclear accidents are estimated:

Hiroshima, black rain	400 mSv
Windscale (UK), 10 km distance	80 mSv
Harrisburg (USA), in the town	1.6 mSv
Pripjat (USSR), town near Chernobyl	100-200 mSv
Kiev (USSR), $\sim$100km from Chernobyl	80 mSv
Contaminated part of Europe, outside USSR	1 mSv
Hungary (average), 800 km from Chernobyl	0.45 mSv

The Japanese-American study concerning the delayed effect of the Hiroshima and Nagasaki bombs indicates, that the lethal cancer and leukemia risk may be $50\cdot10^{-6}$ per mSv dose. – (This view is recently under attack: evidence seems to show that areas of higher geological radioactive background do not show higher cancer mortality, which may indicate a sensitivity threshold: the cancer risk may begin to increase only above a few mSv. But this argument is far from being universally accepted.) – This means that average lethal cancer risk, due to Chernobyl, for Europe amounts 10 per million persons or less. For North Africa and South-East Asia it is 2 per million persons or smaller These numbers may be compared to the risk of dyring of cancer anyway: 20%. (For Hungary, the average 0.25 mSv corresponds to 22 per million persons or smaller, which is the same as the cancer risk of smoking a pack of cigarettes, having a chest X-ray or flying from Budapest to New York.)

It seems that we may sleep quietly even in Central Europe. May we? A risk of one per millions is small, but if there are hundreds of millions or thousands of millions of people affected (see figure 9), the collective loss (risk·population) runs to thousands. A rough estimation says that the collective dose received by the European population of 500 million be about 300 mSv· million people, leading to an estimated number of delayed victims which may reach thousands. The same amount of collective dose was received in the USSR and outside Europe, giving 600 mSv· million people globally, corresponding to the extimated collective risk of 30 000. Thousands of people to be killed by the Chernobyl accident or in Bhopal at the chemical accident are not something what we can live with, even if these numbers is smaller than that of the victims of the Hiroshima bomb or the Second World War or the last wars in Asia or the present fighting in Yugoslavia.

The Future of Nuclear Power

It cannot be the goal of this paper to discuss all the public impacts of the Chernobyl accident. The lessons concerning the design of nuclear power stations can be summarized as follows:

A. Do not use overmoderated reactors. In the case of those already operating the ^{235}U enrichment has been inreased, suppressing the *moderator/fuel* ratio, thus shifting the system to the undermoderated region.

B. Prefer the smaller reactors, for which the release of radioactivity even in the case of worst accident can be confined in the containment building, strengthened against overpressure.

C. Shorten the reaction time of control by blowing gaseous reactor poison gas in, by fast flooding with baronated water, possibly not by pumps, but by the action of gravity.

D. Place the reactors underground, as proposed by Andrej Sacharov and Edward Teller; this prevents atmosphericc contamination even in the case of underground nuclear tests.

E. Make the automatic control inherent, simple foolproof. Remember the statment of the Hungarian-born John Kemény, chairman of the Presidential Commission, investigating the Three Mile Island accident: "The plants can be mode safe. It is the people, who are not."

The Lesson of Chernobyl

According to the present Hungarian high school curriculum, in the last year of the high school, every student learns nuclear physics for about 1-2 months in the early spring. In March in many schools Geiger-Müller counters were used to measure the half life of the ^{137}Ba excited state, dissolved from a commercial solid ^{137}Cs source. (^{137}Cs is inexpensive, being a common fission products in reactor.) This experiment presupposes measuring the background activity in the class room at first.

When the morning radio news announced that the Chernobyl air contamination reached Hungary (Monday, 3 May), the students were queuing in front of the Physics tab of the school already at 7.30, demanding from the arriving physics teacher: "Let's measure the background now!" It was measured immediately at 8 o'clock; it turned out to be three times higher, than last time in March. "Let's open the window! Let's the radioactive air come in!" The window was opened, the activity was measured again. It dropped!

The explanation: during the night the radon (emanating from the brick walls of the building) accumulated. (Brick always contains traces of uranium and its decay products.) This indoor radon was removed by the ventillation. These student never forget this lesson: we live with radioactivity, and the inhaled radon (about 1 mSv/year) gives us a larger dose than that having come from Chernobyl (0.45 mSv).

In those days the physics teachers were the most important and reliable persons in the eyes of the Hungarian youngsters. Our department gave them information withim 4 days (before the end of the Soviet news-black-out): what kind of reactor that one in Chernobyl was, what could be the course of events, what is the estimated amount of released radioactivity, and what to watch in schools . So the students measured the activity of the shoe soles (and they immediately changed to slippers when entering their apartments), they measured the activity of the soil and grass at the outflow of rain pipes, they measured the activity of lettuce before washing it and after (and advised Mom to wash everything carefully), they consumed less mushrooms and strawberry that spring, but they bought the (understandably very cheap) spinach if the activity could be washed off. They even critized the authorities for throwing away the ^{131}I-contaminated milk (why not making cheese out of it, to be sold after 3 months when ^{131}I has decayed away?). They watched the activity fading slowly during has June. Finally they added 0.45 mSv to their personal table in the physics practice book "M., radioactive dose collected in this year."

Now nuclear physics is perhaps the most popular chapter in the high school physics book. The Geiger counter is one of the most popular demonstration tool for the teachers. A radon-monitoring school-network has been developed (on the side of the acid-rain-monitoring network).

With the help of the vice-chancellor of the Gorki Pedagogical University in Kiev, our Department had obtained a permission to visit the Chernobyl Power Plant in late 1991. Several Hungarian high school teachers were included in the group. We measured several μSv/h activity during our one hour long visit at the sarcophagus of Reactor 4 and on the corridor of the building of Reactors 3 and 4. About 1μSv/h or less was the activity in the 10 km closed zone. The activity in the 30 km evacuated zone – 5 years after – has been rather well cleaned up.

The independent international team of experts – organized by the International Atomic Energy Agency – has confirmed that "the protective measures planned or taken for the longer term, albeit well intentioned, generally exceed what would have been strictly necessary from radiation protection point of view." The remaining activity (mainly due to ^{137}Cs) is tolerable outside of the evacuated zone. It certain areas the evacuation did psychologically by moving old farmers from their more harms village than the late radiation dose could produce.

The consequences of Chernobyl are mostly of psychological nature. The number of artificial abortion climbed by about 40 000 in Europe (e.g. in Sweden, Greece). Environmental movements tried to prevent a Hungarian village, Hajmáskér, to accept Ukrainian children from recovery in an abandoned Soviet garnison "because the local population may be infected by radiation" (a pure scientific nonsense), but in a referendum the population of the village decided in favour of the Ukrainian children. The Chernobyl card was overplayed by Ukrainian nationalists as well, but international investigations have shown that the medical state of the country people is not better in the unaffected parts of the country either. Scientists are watching whether any significant excess radiation risk can be detected in any type of sickness in the Chernoby region (what would be a valuable lesson to e learned), but there is low chance for it. (Perhaps the thyroid cancer of children will be the only exception, produced by the ^{131}I activity of the first weeks, transferred by the milk of caws, gazed on the fallout-polluted North-Western swamplands. The milk produced by the cooperatives with more advanced agricultural feeding in other directions did not have this harmful ^{131}I excess.)

Chernobyl was not an accident. It was a catastrophe. The released active ^{137}Cs nuclei are with us for decades (as the active ^{90}Sr nuclei, released by atmospheric bomb tests are). But now we have become convinced, that opornes and understanding pays off better then secrecy or panic. We see that concepts of nuclear physics, positive and negative feedback, inherent instability and stability, probability, risk and global responsibility can be taught to a wide sector of the youth population. We hope that the new generation can be trusted in the coming decades more than ours in the past decade could.

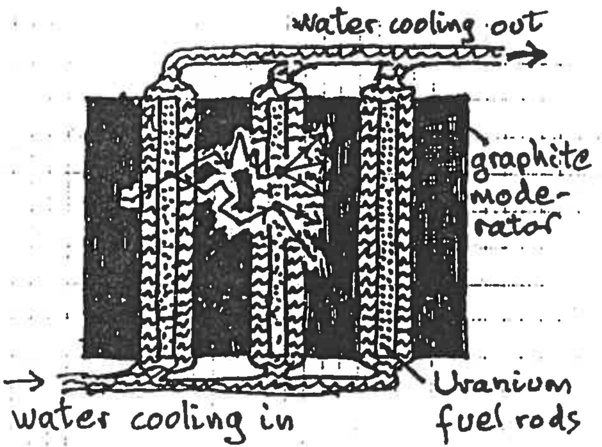

Figure 2. Neutron produced in fuel rod slows in graphite, splits again in fuel rod.

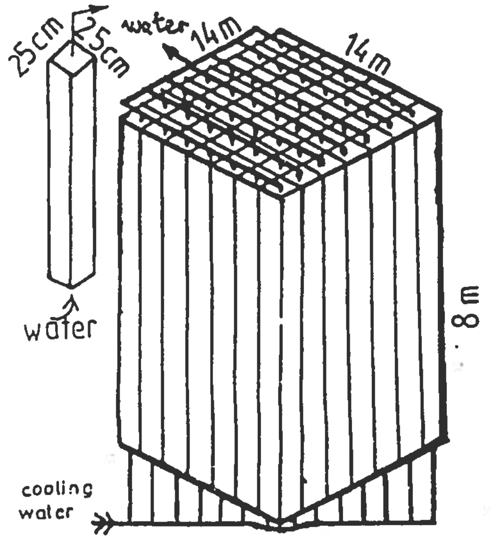

Figure 3. Scheme of the Chernobyl reactor built up of 1693 units.

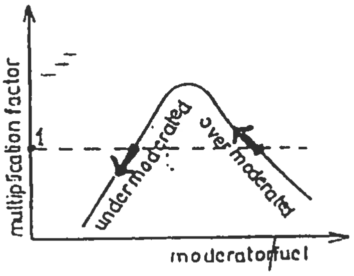

Figure 1. Stability conditions for undermoderated and over-moderated reaktor

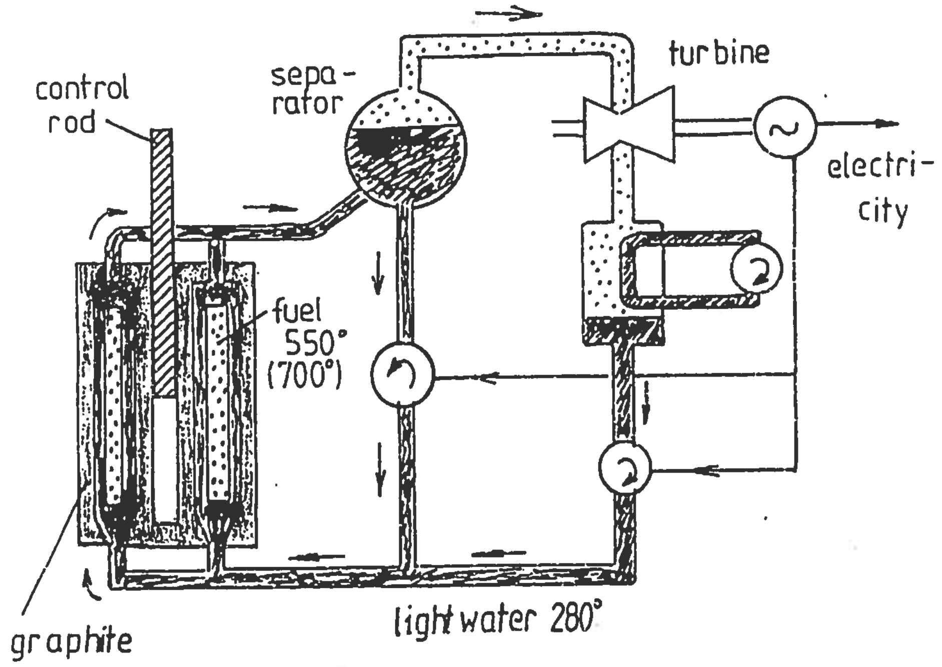

Figure 4. Water network in the Chernobyl reactor

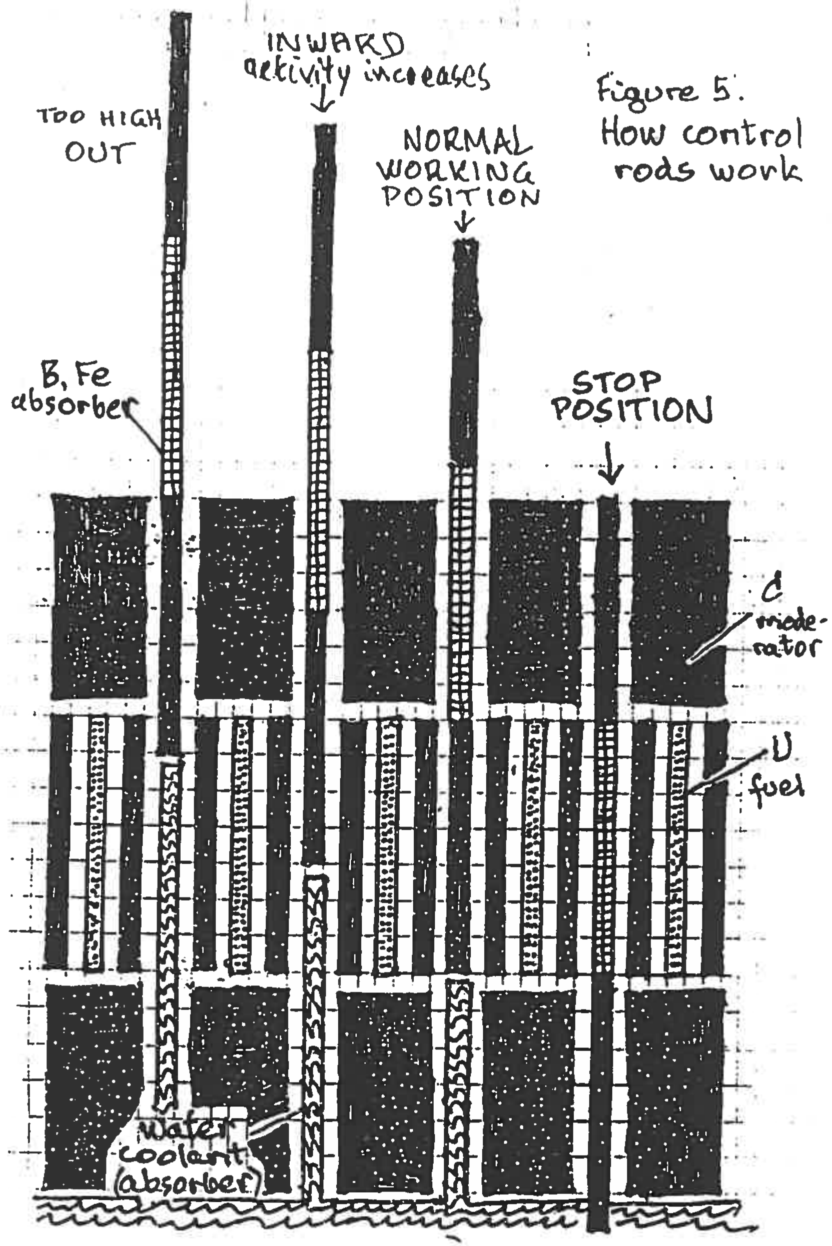

Figure 5.
How control
rods work

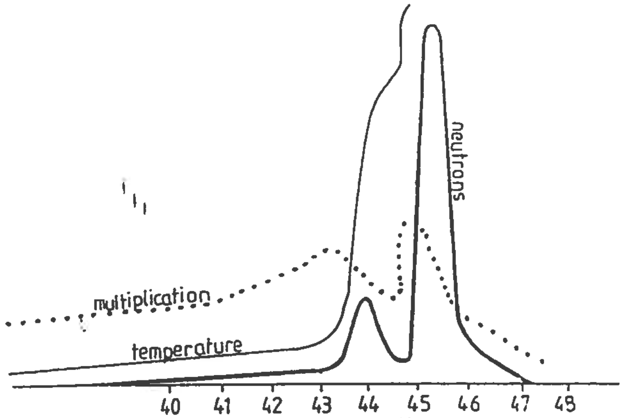

Figure 6. Computer-reconstruction of the events in the last seconds

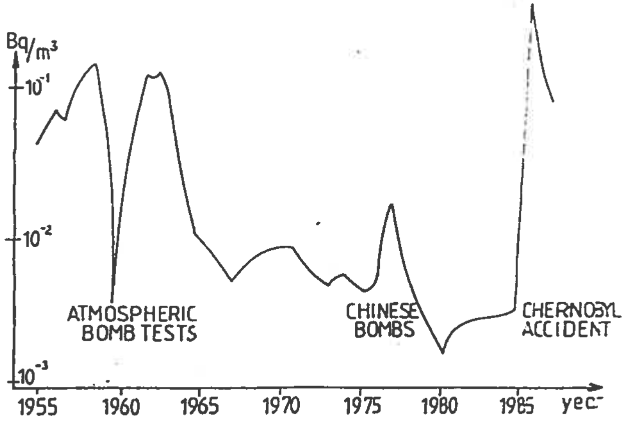

Figure 7. Yearly average air contaminations in Hungary

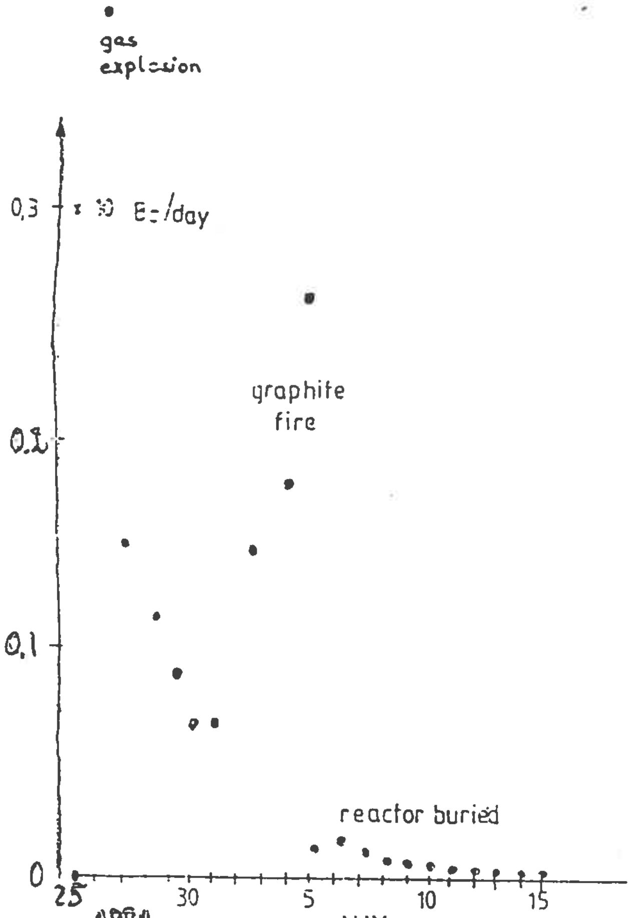

Figure 8. Radioactivity release from Chernobyl

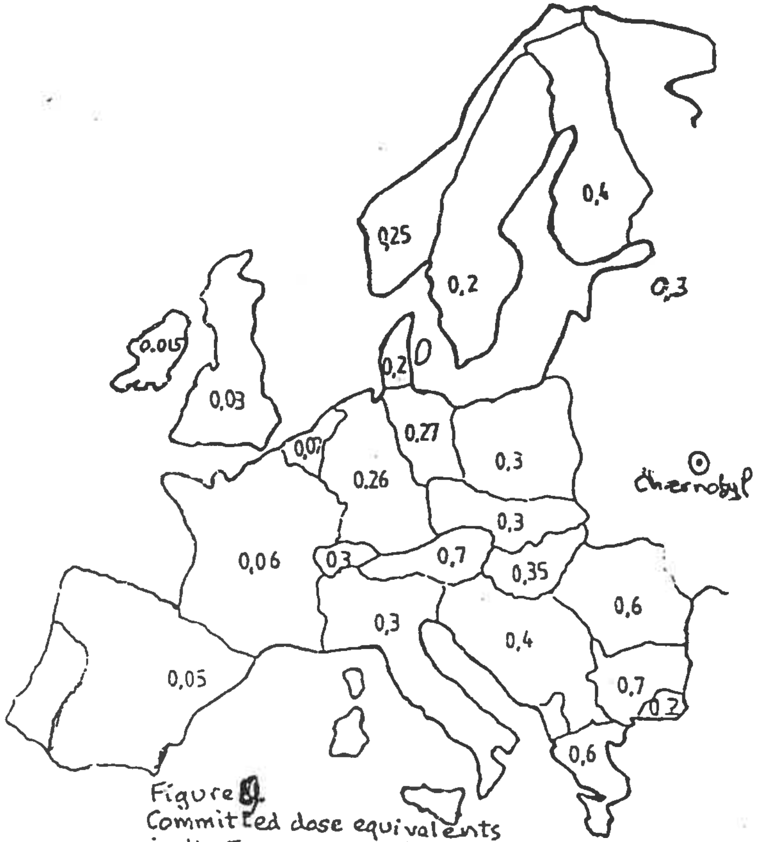

Figure 9.
Committed dose equivalents
in the European countries in mSv