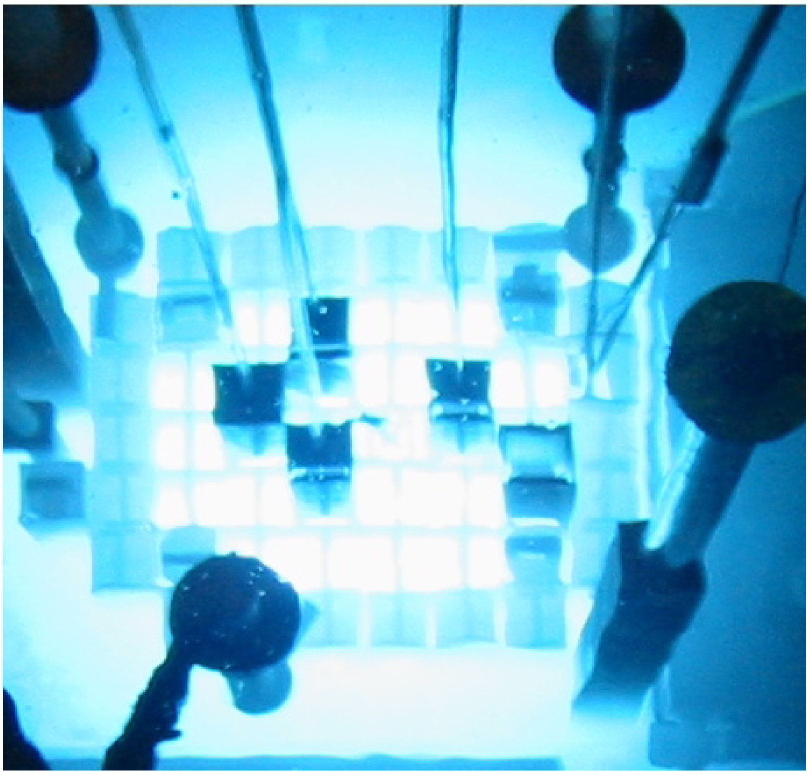

NUCLEAR TECHNOLOGY IN ENERGY GENERATION

NUCLEAR POWER IN POLISH ENERGY POLICY

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In view of the present situation in Polish electric system the option of nuclear power was accepted by Polish Government. The results of relation between the consumption of electric energy and Gross Domestic Product (GDP) calculated using Exchange Ratio (ER) for European countries (Fig. 1) show that economic development in Poland should be accompanied with growth of electricity consumption.

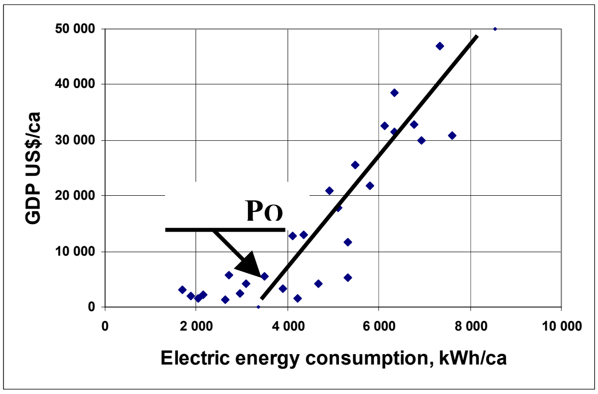

Fig. 1. Relation between GDP per capita annum and electric energy consumption (netto) for European countries in 2003.

The coefficient of installed electric power utilization in Poland is in the range of this parameter for other European countries. Thus, the growth of electricity production will be achieved by construction of new electric power stations and will be connected with growth of energy raw material consumption.

The density of primary energy consumption in the European region is the highest in the world:364 toe/km^2 (tons of oil equivalent) in comparison with North America– 124 toe/km^2 and world mean value – 72 toe/km^2 [1]. In Europe, and especially in the European Union countries, high attention is paid to limitations of emissions of harmful gases from electric power generating stations. Limits of SO_2, NO_x and CO_2 emissions were included in the Poland accession treaty into the EU. These values are also limited by EU Directives e.g. 2001/80/EU.

The electric power generation system in Poland is based mainly on coal combustion. In the first three quarters of 2005 the share of coal (hard and brown) in electricity generation was 94,4% [2]. The rest of consumption was covered by gas and renewable energy sources (water, wind and biomass). Therefore, Poland is a source of most harmful compound emissions in Europe. Substantial share of existing electric power generation stations have been in operation for more than 30 years [3]. Modernization of these facilities to achieve EU emission limits is uneconomic. Thus, these plants should be closed and replaced by new ones. New plants will operate for the next 40 ÷ 50 years. Therefore, the selection of technology for electricity generation should be based on forecast of energy raw materials availability and their price over the power plant operating time, taking also into account the environmental protection limits determined by the European Union. In this situation one of possible profitable solutions will be a nuclear power plant.

The properties of new generation nuclear power stations (operating, ready for construction or in design state) are thoroughly discussed in DoE document [4]. From analysis of electricity generating cost projections for year 2010 for nuclear, coal and gas technology for selected countries it is clear, that in most cases the cost of nuclear energy is comparable with coal and much cheaper than gas and renewable energy sources [5].

The review of future nuclear reactor designs is presented, stressing their capability to enhance uranium utilization, major effectiveness of electricity generation and possibility to supply energy for chemical processes e.g. for hydrogen production. The technology of high temperature helium cooled reactor, fast breeder reactor and accelerator driven system were presented in [6].

The analysis of radioactive waste and spent nuclear management technologies were presented based on [7]. It is shown, that there exist proper technologies for safe, economical acceptable management of spent fuel and radioactive waste from operation and decommissioning of nuclear power plants and auxiliary facilities.

The ideas of nuclear transmutation of long lived isotopes in spent fuel and research development in this field were presented.

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EVOLUTION OF NPP SAFETY RULES INCLUDING ADVANCED GENERATIONS OF THE NUCLEAR ENERGY SYSTEMS

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In the paper [1], best practices related to the development of the nuclear power plant (NPP) safety rules have been identified. A worldwide consensus is in progress. The feedback of experience from present-day plants will be incorporated into future plants so that they can safely and efficiently contribute to future energy needs.

For most existing NPPs safety rules were based initially on the requirement that the plant be shown to withstand a set of postulated accidents named design basis accidents (DBAs). Generally, the most severe of these was a loss of coolant accident (LOCA) caused by a double ended failure of a main coolant pipe. A set of extensive requirements were developed which specifically set deterministic methods for analyzing the behaviour of plants to ensure that certain parameters, such as fuel clad temperature, were not exceeded. These considerations resulted in the requirement that plants be equipped with emergency core cooling systems (ECCS). From the beginning, the concept of “defence in depth” was developed to ensure that multiple barriers were provided to prevent the release of fission products to the environment. The final barrier was the containment system, which was required to withstand the maximum design basis accident.

In the seventies, it was recognized that probabilistic safety analysis (PSA) could provide significant insight into the safety of nuclear reactors. PSAs indicated that significant contributors to risk involved accidents other than traditional DBAs. These insights were substantiated by the severe accident at TMI-2, and the Chernobyl disaster.

PSAs provide the means to address the severe accident scenarios, as their risks can be quantified and decisions about the extent to which they should be mitigated by design or operational modifications can be made rationally. In addition to severe accidents some complicated situations such as anticipated transients without scram (ATWS) or shutdown state events need to be addressed beyond the traditional approach of design basis accidents.

In general, significant consensus already exists in the area of fundamental safety principles and rules. Advanced reactor designs include both the requirements necessary to meet the traditional regulations with conservative, licensing-based methods and additional provisions to deal with severe accident prevention and mitigation. The agreement appears in advanced designs as well as in the requirements (INSAG, URD, EUR).

There are two main lines of the advanced PWR programs: large "evolutionary" plants such as the ABB-CE System 80+, the Japanese APWR, the French N4, the EPR, and smaller "passive" designs such as the Westinghouse AP600.

The American EPRI and the European EUR utility recommendations require that high pressure core meltdown situations must be prevented. With reference to INSAG-3, it is intended that the improvements in defence in depth should lead to a global core melt probability of less than 10^{-5} per plant operating year This ensures that the maximum conceivable release would necessitate only very limited protective measures in space and time and that neither permanent relocation nor emergency evacuation would be necessary outside the immediate vicinity of the plant. These objectives imply that substantial improvements be made to the containment function.

The French-German approach applied in the EPR project surpasses current evolutionary developments. One of the fundamental aims is the "practical elimination" of accident situations which would lead to large early releases such as containment bypass, shutdown states and open containment building, reactivity accidents, high pressure core melt, depressurization of the RPV or global hydrogen detonation. When they cannot be considered as physically impossible, design provisions have to be taken to "design them out".

The principles generally in use at present, especially IAEA suggested principles, are heavily biased toward Light Water Reactor design practices where active defense in depth is essential. Application of these principles to the new generation of the NPPs such as High Temperature Gas Cooled Reactors (HTGR), which are characterized by inherent passive features, would result in considerable overdesign and might even impact negatively the overall safety of these designs.

For HTGRs represented by the Pebble Bed Modular Reactor (PBMR), the defence in depth definitions have been developed to show compliance with existing principles, but with a different emphasis on the importance and execution of the various levels of defence in depth as suggested by the IAEA.

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GAS COOLED REACTORS - A NEW PROPOSAL FOR POWER INDUSTRY

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Gas cooled reactors are not a new project. The new designs have been tested for almost 50 years. They were used by power industry of the USA, France, Germany and the UK. Due to several political and financial reasons the program of their development has been stopped in Europe and now the progress of that family of reactor systems is achieved mainly in Far East countries and South Africa. The know-how elaborated in Germany is now being developed in China and South Africa. American technologies are employed in Japan. Gas cooled reactor systems seem to be safe, reliable and inexpensive, capable to work in high temperatures. They are the hope of the power industry for the nearest future.

There have been built two test reactors on which the new technology of High Temperature Gas-cooled Reactors (HTGR) are object of experimental work. The first – the Japanese High Temperature Test Reactor (30 MW of thermal power) uses helium as the coolant, ceramics as coating for fuel particles, and graphite as the reactor core structural material. The fuel particles are spherical and less than 1 mm in diameter. The fuel kernel of the particles is made of uranium oxide or carbide and coated by four thin layers of special carbon and silicon carbide ceramic to protect the kernel and prevent it from releasing products generated by nuclear fission. Kernels coated with carbon and silicon carbide (SiC) have greater heat-resistance than those coated with metallic materials, and do not melt down even at temperatures above 1000ºC. Helium is used to cool the reactor core, it reaches about 950ºC. Graphite is used as structural material in the HTGR core. It moderates the generated neutrons and has useful properties such as low neutron absorption, minimal radiation damage, superb heat resistance and high thermal conductivity. The graphite function is to protect the fuel and maintain fission reaction by neutron moderation. In Japan there have been conducted conceptual design studies of HTGR of rated power from 50 MWe to 600 MWe. The studies showed that the construction of modular type HTGR is feasible using technologies proven in the operation of HTTR and that a large size HTGR, such as a 600 MWe plant, is the best from economic point of view. It is expected to be competitive with the Light Water Reactor plant.

The second test reactor – HTR-10 - was built in China. It is the first step of the HTGR development strategy in China. The objective of the HTR-10 is to verify and demonstrate the technique and safety features of modular HTGR and to establish an experimental base for developing the nuclear process heat applications. The HTR-10 is a pebble bed type, 10 MW thermal power, high temperature gas-cooled reactor (700 ºC core outlet temperature). It uses the spherical fuel elements (diameter 6 cm) with ceramic coated fuel particles. The pressure of primary helium circuit is 3 MPa. At the secondary circuit, a steam turbine cycle for electricity and heat cogeneration is designed. Later, in the second phase, the HTR-10 will be operated at the core outlet temperature of 900 ºC. The gas turbine and steam turbine combined cycle for electricity generation is preliminary designed.

In China the prototype HTGR power plant will probably be a pebble bed type HTGR with gas turbine cycle and electric output of 100 MW. The construction is expected to be finished in 2010.

In South Africa a new project of the Pebble Bed Modular Reactor (PBMR) nuclear plant has been under development since 1993. It entails the building of a demonstration reactor project near Cape Town and a pilot fuel plant near Pretoria. The current schedule is to start construction in 2007 and for the demonstration plant to be completed by 2011. The first commercial PBMR modules are planned for 2013. The PBMR is a High Temperature Reactor (HTR), with a closed-cycle, gas turbine power conversion system. The plant is recommended as very efficient, safe and attractive from economics point of view. Similarly as in Chinese HTTR-10, the South-African PBMR uses particles of enriched uranium dioxide coated with silicon carbide and pyrolitic carbon. The particles are encased in graphite to form 6 cm diameter fuel spheres.

In South Africa it is planned to produce 4000 MW to 5000 MW of power from pebble bed reactors. This equates to 40 PBMR reactors of 110 MWe each. It is expected, that in future, the South Africa will export about 10 PBMR reactors annually.

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HEALTH EFFECTS OF LOW RADIATION DOSES

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The results of recent studies in molecular biology and of epidemiological studies among people exposed to increased levels of radiation have been reviewed [1]. The figures developed by the author on the basis of available results support strongly the thesis that low radiation doses obtained at low dose rates are not harmful to human health. Among them the most convincing are the studies of nuclear workers in various countries, exposed to low dose rate radiation over several years. This study, conducted by the International Cancer Institute, with data on 100 000 workers, showed that the doses up to 300 mSv involve no detrimental health effects [2].

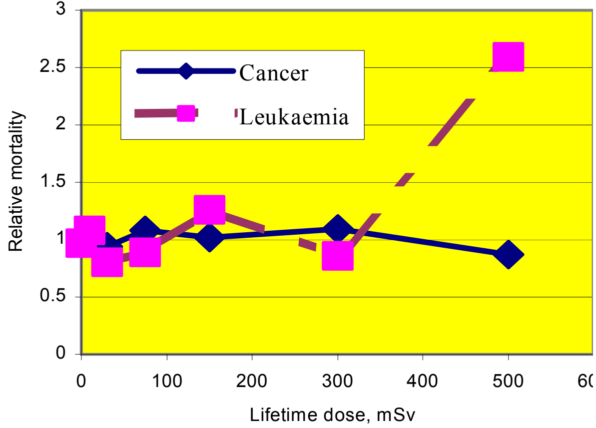

Fig. 1. Radiation effects on nuclear workers (data from [2]).

Since "healthy worker effect" is frequently quoted as the reason why people working with radiation show lower frequency of cancer, a study of 28 000 shipyard workers [3] has been reviewed and the results correlated with the health of other shipyard workers who had no radiation exposure.

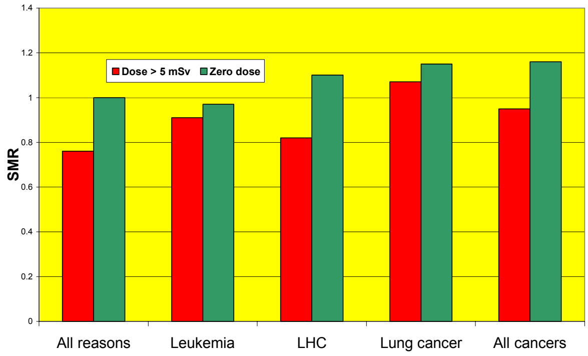

Fig. 2. Mortality for shipyard workers in Shippingpor (data from [3]).

The results show that the standard mortality ratios (SMR) for cancer and leukaemia among workers exposed to low radiation doses were lower than among those who were not exposed to radiation (Fig. 2).

The difference between the detrimental effects of radiation obtained instantaneously by Atomic Bombing Survivors (ABS) and low radiation dose rates obtained by workers or medical patients at the same absolute values of radiation doses was based on the review of results obtained in radiotherapy of 64 172 patients in Canada [4].

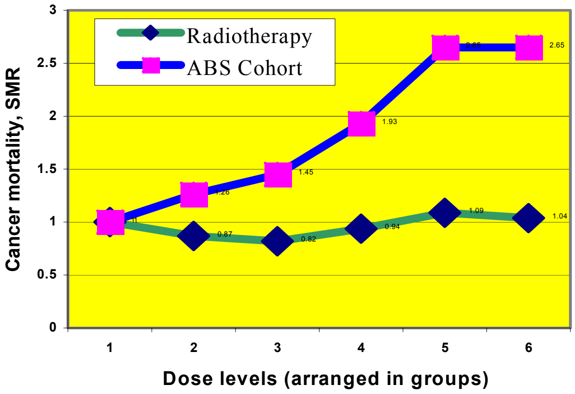

Fig. 3. Health effects of low rate radiation doses in radiotherapy vs. atomic bombing, data from [4].

While the doses obtained instantaneously during atomic bombing resulted in increase of cancer mortality in ABS cohort, the same doses obtained at low dose rates resulted in decreased cancer mortality (Fig. 3).

The results of the latest molecular biology studies have shown that low dose rate radiation stimulates natural defense mechanisms. This results in more effective defense against all forms of cancer. Since the fraction of cellular damage due to radiation is only a miniscule fraction of all damages, the enhancement of capability to eliminate cancerogenic effects is much more important than the minimally increased fraction of cell damages. This position is taken by various highly competent experts and academies [5].

The author formulated a set of comments to the recent UNSCEAR document on Effects of Ionizing Radiation on the Immune System, which were adopted by the Polish delegation to UNSCEAR and submitted in the discussions [6].

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RADIATION DOSES IN NORMAL OPERATION OF NUCLEAR INSTALLATIONS

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The surveys [1, 2] show that the radiological releases during nuclear power plant (NPP) operation have been steadily reduced and are presently much below the requirements of standards and regulatory authorities.

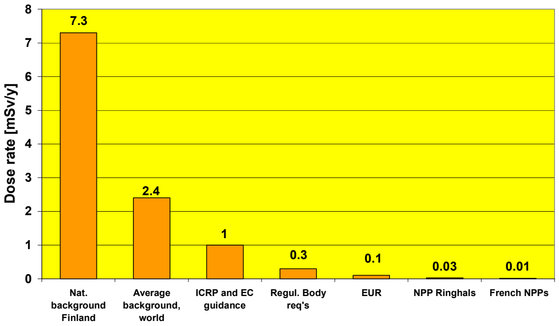

Fig. 1. Comparison of radiation doses due to NPP operation with the average natural background and dose limits [1].

A comparison with the natural background reveals that the doses due to NPP operation are a negligible fraction of the natural background variation (Fig. 1). In spite of that, the nuclear industry applies the principle of reducing radiation doses as low as reasonably achievable (ALARA) and although the doses are much below requirement limits, they are being further reduced.

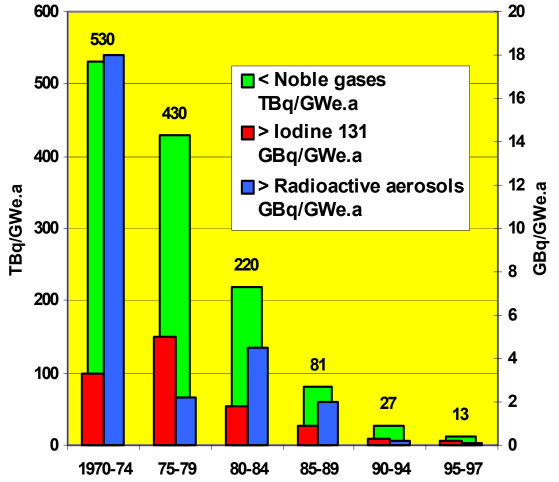

Fig. 2. The reductions of emissions from PWRs [2].

While the emissions in the period of 1970-74 were within admissible limits, the emissions nowadays are many times smaller (Fig. 2). The results of health studies around NPPs [3] and other nuclear installations have shown no detrimental health effects. In particular the two large studies on reprocessing facilities are reviewed, one for Sellafield the other for La Hague. The releases from these facilities have been strongly reduced (Fig. 3).

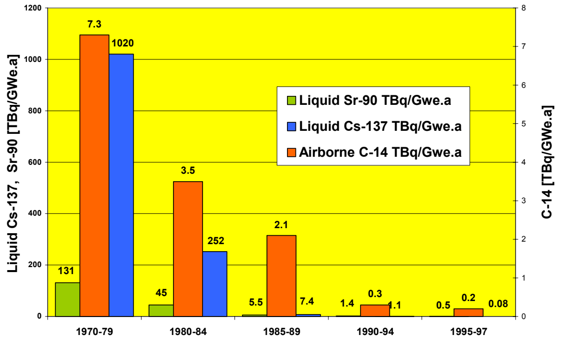

Fig. 3. Reduction of releases from fuel reprocessing plants [2].

According to the studies conducted in the UK; by COMARE and in France by a special committee convened by the ministers of health and of the environment, the releases from La Hague could have caused over the whole history of the plant operation and in the whole exposed area less than 1/1000 of leukaemia cases [4].

The health effects of radiation releases from NPPs are shown to be negligible. The reasons for this success are reviewed, and the influence of barrier system is stressed. Its effectiveness is shown on example of Mochovce NPP (with WWER 440/213 reactor, the same as was under construction in Poland), e.g. in the case of iodine I-131, if the content in the fuel is normalized as 1, then in the fuel-cladding gap it is 0.01, in the primary coolant 10^{-5}, in the containment air 10^{-9} and the fraction of I-131 which is daily released to the atmosphere outside containment is less than 10^{-11}. Thus the limitation of NPP releases does not rely on just one barrier, or one filter, as in a coal fired plant. It is made up of several successive and highly effective barriers, so that even in the case of failure of one of them the system remains effective [5].

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EU NUCLEAR RISK ASSESSMENT RESULTS

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The results summarized below were presented in the invited paper at the symposium of the European Union in Brussels on Security and Safety of Energy Infrastructures in Comparative View and fully accepted. They are of high significance, showing the position of EU experts on the relative risks of nuclear power [1].

The effects of radiological risks of nuclear power have been reviewed in the light of recent studies conducted in the European Union. It shows that the radiological releases during normal NPP operation have been steadily reduced and are presently much below the requirements of standards and of regulatory authorities.

The review of results of recent studies in molecular biology and of epidemiological studies among people exposed to low levels of radiation [1-3] supports the thesis that low radiation doses obtained at low dose rates are not harmful to human health.

The review of accident hazards in NPPs shows that the safety goals established for nuclear power have been reached and the hazards minimised far below the limits (Fig.1). The new designs of NPPs fully implement not only the safety principles recommended by the IAEA, but also the recent recommendations of EU Technical Support Organisations to Regulatory Authorities and the European Utility Requirements [1].

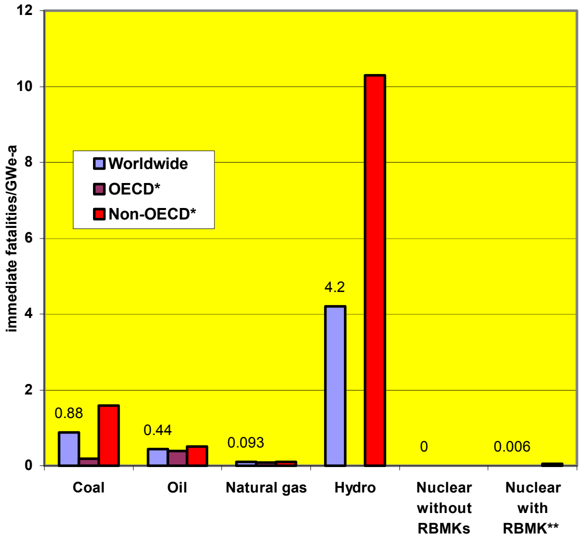

Fig. 1. Hazards of severe accidents in energy chains.

This means that the design of new NPPs ensures practical elimination of core melt in shutdown states with open containment, high pressure core melt, core melt with containment bypass, large early releases resulting from containment failure and mitigation of low pressure core melt and vessel melt through.

A review of the measures applied nowadays in the design and operation of the NPPs shows great progress made not only in the new designs, but also in safety upgrading in existing NPPs.

Comparative studies of health hazards due to accidents in various energy cycles show that nuclear power is one of the safest. The accidents such as in Chernobyl cannot occur in the NPPs of today.

In addition, the studies of effects of Chernobyl accident have shown that the initial fears of radiation effects were highly exaggerated. In addition to 32 deaths of emergency workers in the early stage of the accident, there have been 9 deaths of children due to thyroid cancer, but otherwise there has been no increase of solid cancers, leukaemia or genital malformities, and no hereditary effects have been detected.

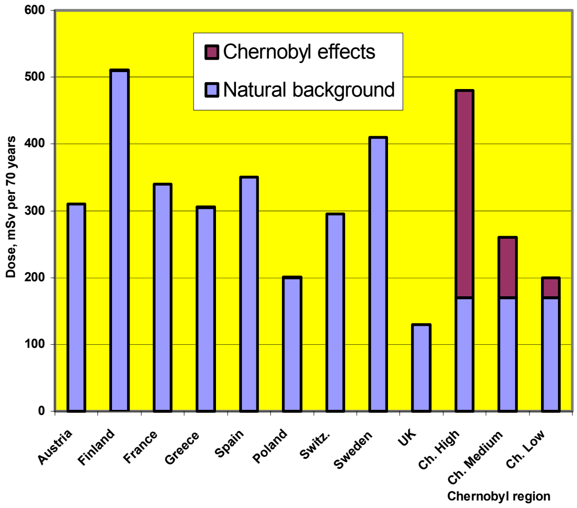

Fig. 2. Lifetime radiation doses in various regions of Europe.

A comparison of radiation doses in the region around Chernobyl with the doses in various EU countries shows that the lifetime doses in so called “High dose” regions are LOWER than the average doses in Finland and in several European regions (Fig. 2). The decisions of evacuation of people and of inclusion of several millions of inhabitants into the list of “Chernobyl victims” were unjustified and would not be taken in the light of present knowledge.

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EXTERNAL COSTS OF ELECTRICITY PRODUCTION IN EU COUNTRIES

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The review of comparative studies of health hazards due to accidents in various energy cycles shows that nuclear power is one of the safest. The accidents such as in Chernobyl cannot occur in the NPPs of today [1].

Comparisons with other energy sources show good safety record of NPPs built and operated according to nuclear safety principles.

In particular the comparison of accident risks shows that NPP with water moderated reactors, which are the dominating type today and will be built in Poland, enjoy the best record of health among all energy sources.

In contrast to the small radiation doses from nuclear fuel cycle, the pollutants emitted in fossil fuel cycles result in pollution levels much above the natural background and clearly detrimental to human health. Extensive comparative studies of external costs due to various energy sources conducted by EU experts have yielded results indicating that the nuclear power is one of the safest and cleanest sources of energy.

The estimates in the EU study of external costs of energy production (ExternE) are made not only for the stage of electricity generation, but for all stages of the fuel cycle, from the birth to the grave (Fig. 1). In the case of nuclear power this means that both uranium ore mining and uranium enrichment, just as nuclear fuel reprocessing are included in the evaluation.

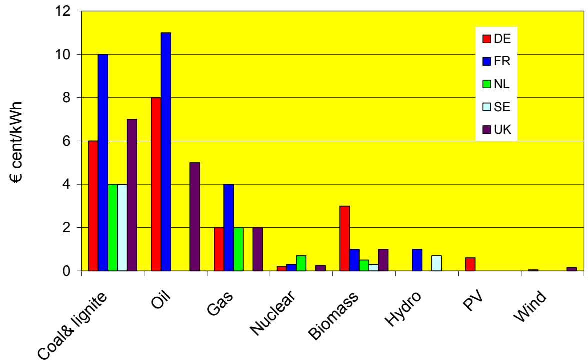

Fig. 1. External costs for electricity generation in EU countries [2].

In the case of coal or gas the health damages at the stage of mining and transportation are significant. In the case of solar photovoltaic cells (PV) the releases due to production of the cells result in health hazards much higher than those for nuclear power. The graphic comparison of health effects based on data from [3] shows that nuclear power is among the safest and most human friendly sources of energy.

Recent studies of health effects of air pollution due to fossil fuel burning in the EU have shown, that the introduction of measures aimed at reduction of air pollution can bring a significant extension of average human life in the EU.

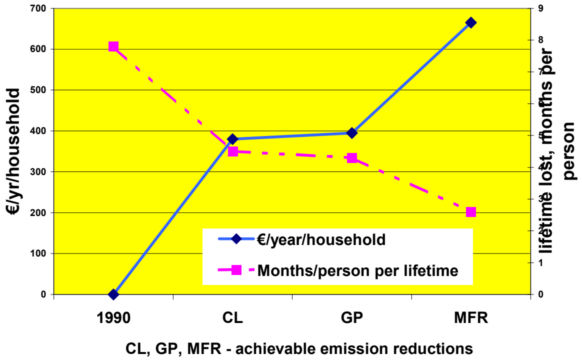

Fig. 2. External costs of electricity generation in EU[2].

In Fig. 2 the symbols CL, GP and MFR represent reduction of air pollution which would be achieved applying current legislation- (CL), or the guidance of Gothenburg protocol (GP), or using Maximum Feasible Reduction (MFR). It is seen that the emissions of air pollutants in 1990 in the EU countries caused life shortening for an average EU inhabitant by 7.8 month due to breathing polluted air. If the air is cleaned according to MFR an average citizen of EU can gain 5 months of lifetime. It would be a significant achievement for each and everyone of us [4].

Introduction of nuclear power, which does not cause any air pollution nor global warming, is one of decisive measures for assuring clean air and healthy life in the European Union. The EU assessment of nuclear risks shows nuclear power to be a safe and reliable energy source.

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CHEMICAL ACTIVITY OF NOBLE GASES Kr AND Xe AND ITS IMPACT ON FISSION GAS ACCUMULATION IN THE IRRADIATED UO$_2$ FUEL

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It is generally accepted that most of the insoluble inert gas atoms Xe and Kr produced during fissioning are retained in the fuel irradiated at a temperature lower than the threshold. Some authors assume random diffusion of gas atoms to grain boundaries and consider the effect of trapping the atoms at inter-granular bubbles until saturation occurs. Others confirmed that bubbles tend to concentrate in the grain boundaries during irradiation. Likewise, some authors further assume that most of the gas atoms are retained in solution in the matrix of grains being there immobilised or are precipitated into small fission gas bubbles.

The experimental data presented in the open literature imply that we can assume that after irradiation exposure in excess of 10^{18} fissions/cm^3 the single gas atom diffusion can be disregarded in description of fission gas behaviour. It means that significant fraction of fission gas products is not available for diffusion. This is a general observation for the whole temperature range of UO_2 fuel that is exploited in the light water reactors (LWR). The above well documented assumption implies that a single gas atom diffusion model cannot be used to estimate the amount of fission gas that will be released from UO_2 during irradiation

Out of pile experiments show that during annealing the irradiated UO_2 samples bursts of fission gas release occur. After a small burst release at relatively low temperature, a large burst release appears at high temperature.

The point defects induced by radiation begin to recover at 450 – 650 ^{0}C and are completely almost recovered above 850 ^{0}C, while defect clusters of dislocations and small intragranular bubbles require 1150–1450^{0}C.

Thermal recovery of radiation defects and microstructure change in irradiated UO_2 fuels studied by X-ray diffraction and transmission electron microscopy leads to the conclusion that the gas release kinetics from irradiated UO_2 is determined by the kinetics of thermal recovery of the radiation induced defects.

If the point defects, defect clusters of dislocations and small intra-granular bubbles are thermally recovered at the temperatures below 1450 ^{0}C, a natural question concerns nature of forces which immobilise the noble gases. Hence an additional trapping process of inert gas atoms with the uranium dioxide material is suspected to occur.

The process of strong binding of the fission gas fragments with the irradiation defects is described in the literature as a process of chemical interaction with UO_2.

It is assumed further that the vicinity of the fission fragment trajectory is the place of intensive irradiation induced chemical interaction of the fission gas products with UO_2.

We can further assume that above a limiting value of fission fluency (burn-up) a more intensive process of irradiation induced chemical interaction occurs. Significant part of fission gas product is thus expected to be chemically bound in the matrix of UO_2.

From the moment of discovering the rare gases (helium, neon, argon, krypton, xenon and radon) at the end of XIX century until to the beginning of sixties years of XX century it was considered that the noble gases are chemically inactive.

The nobility of rare gases started to deteriorate after the first xenon compound was found by Barlett in 1962 [1]. Barlett showed that the noble gases are capable of forming what one could consider as normal chemical compounds, compelling chemists to readjust considerably their thinking regarding these elements.

In a burst of activity in the years that followed after the discovery of the first halogen compound, a number of compounds of noble gases have been reported, especially with xenon. It is observed, that the rare gases make reaction with the most electronegative elements, such as fluorine and oxygen. Later it has been shown that Xe (sometimes Kr) form bonds also with other non-metals, and even with some metals.

While many of these can be regarded as metastable species, several are actually thermodynamically stable compounds and can be obtained commercially.

There is very interesting report on bonding between noble gas atoms and an actinide metal atom uranium.

Experiments with mixture of noble gases using the infrared spectroscopy (IR), coupled with theoretical calculations, provide strong evidence for direct bonds between Ar, Kr, or Xe atoms and the U atom of the CUO molecule.

The authors believe that the experimental and the theoretical data presented in their report make a strong-case for the interactions between the U atom of CUO and the noble gas (Ng) atoms. The U-Ng bond distances are short, and the U-Ng interaction is strong enough to change the spin state of the CUO molecules. Because of the positive charge, the UO_2^{2+} ion, which is isoelectronic with CUO, should form even stronger bonds with noble gas atoms, which could lead to growing number of complexes, that contain direct noble gas – to – actinide bonds.

The examples of rare gas compounds presented above show that noble gas chemistry is much richer than it would be expected. New chemical bonds between strange bedfellows, like noble metals, actinides and noble gases, can still be found.

Since the examples of rare gas compounds presented above are formed by applying the classical chemical methods, the more the noble gas spices in the conditions of neutron and fission fragments irradiation of the UO_2 fuel type can be expected [3].

This assumption is suggested by the fact that the ClXeCl has been found to form after irradiation with 501.7 nm laser light of Cl_2-doped xenon matrices. It appears that after excitation of the Cl_2 there is little or no barrier for the rearrangement to ClXeCl [2].

The fission fragments are striped of about 20 electrons along most of their paths in the medium in which the fission takes and are still 10 near the end of their paths.

Fission fragments are at the same time very energetic and highly charged particles; they interact strongly with electrons of the material losing their energy mainly by ionisation but also by elastic collisions with atoms as a whole.

Keeping in mind that the UO_2 fuel is highly defected, ionised with very energetic and highly charged fission fragments, it appears that during irradiation there is little or no barrier for the formation of rare gas atoms compounds with the UO_2 molecule and fission products. There would be a strong interaction between the U atom of UO_2, fission products and the noble gas (Ng) atoms. This further implies that significant part of the fission fragments after dissipating all their energy and stopping in the material being still highly ionised at the end of their paths react chemically with the fuel [3].

It is worth to be noted that the inert gases Kr and Xe are practically not formed directly by fission, but originate by β-decays from the precursors. Se-85, Se-87, Br-88, and Br-89 are precursors for the krypton and Sn-131, Sn-132, Sb-133, Sb-134, Te-135, I-137, I-138 and I-139 are the precursors for the xenon. That is why the prompt fission yield for the Kr-85m, Kr-87, Kr-88, Kr-89 and for the Xe-131, Xe-133, Xe-135, Xe-137, Xe-138 Xe-139 are equal zero.

This that the inert gases Kr and Xe mostly are not formed directly by fission, but originate from the precursors imply, that the precursors which are not gas atoms can easier chemically react with the UO_2 fuel than the rare gas atoms. We can assume that the precursor already chemically bond with the fuel decaying to the rare gas atom do not change the electron shell of the compound and remain chemically bonded. It means that the rare gas atoms are chemically bound with the UO_2 fuel after decaying of the precursors which chemically reacted with the fuel [3].

Keeping in mind that the gas release kinetics from irradiated UO_2 is determined by the kinetics of thermal recovery of the radiation induced defects and associating it with the idea of the noble gas atoms trapped in clathrates (where no chemical bonds between gas atoms and the surrounding occur), we can postulate that in point defects, dislocation loops and gas bubbles the rare gas atoms with the closed-shell electronic structure can be immobilised. In this sense, there exists no true diffusion for the fission gas in the UO_2 fuel [3].

It appears necessary in this discussion to recall the conclusion of the panel discussion of the International Seminar on Fission Gas Behaviour in Water Reactor Fuels, held in Cadarache, France 26-29 September 2000. Namely "The notion of diffusion coefficient of the fission gas atoms should be verified and if we resign from the term *re-solution* then what we should assume instead".

It is very important to recall also that solubility of rare gas atoms in uranium alloys or ceramics is so low that it has not been measured. In perfect crystals, the order of magnitude of the solubility is 10^{-10} in the most favourable cases. This figure may be increased up to ≈ 10^{-5} in the vicinity of dislocations. So, considering the huge amount of gas immobilised in the UO_2 fuel, the solution process and in consequence the re-solution process of rare gases is to be replaced by the irradiation enhanced chemical bonding process. This explains the huge fission gas accumulation in the irradiated UO_2 fuel [3].

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VISUALIZATION OF BOILING PHENOMENA UNDER THE TRANSIENT FLOW IN ANNULAR PARALLEL CHANNELS

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The variations of flow parameters preceding the occurrence of critical heat flux (CHF) in a vertical channel of annular geometry under transient conditions were studied. Interesting data on the flow visualization during CHF occurrence were recorded with the digital camera Kodak EHTAPRO HS Motion Analyzer with the speed 1125, 2250 or 4500 frames/s.

The experiments were carried out at the water test facility WIW-300. The test section consisted of two concentric pipes with 23/20 mm O/I diameters and of 1000 mm length [1]. In each experimental run at fixed inlet coolant parameters of temperature, differential pressure and flow, the power supply was increased until due to CHF appearance the flow was decreased to zero.

The experiments were performed at inlet coolant pressure about 0.1÷0.2 MPa, temperature 20÷50 °C and downwards flow rate 0.25÷0.50 m^3/h.

The results of selected experiments were recorded. The typical stages of phenomena initializing the boiling crisis were observed and high speed of CHF onset was confirmed [2]. The time between the appearance of the first vapor bubbles on the surface and the boiling crisis is about 1 s. The heat flux initializing the bubble flow corresponds roughly to 0.89 of critical heat flux [2].

The bubble slide velocity was determined from recorded image sequences with the downflow patterns. The initial slide velocity was found to be equal to 0.24 m/s. It was observed that bubbles either lift off directly from the nucleation site or slide initially and then lift off depending on flow and thermal conditions (Fig. 1). It was noticed that the vapour bubble at first slides along the heating surface and lifts off after 0.04 s.

The same observations were presented by Thorncroft [3], who moreover concluded that the process of vapour bubble sliding appears to be responsible for enhanced energy transfer from the heating surface as evidenced by larger heat transfer coefficients for upflow than for downflow under otherwise identical operating conditions.

The work has been accomplished under the project 3 T10B 067 28 of Polish Committee of Scientific Research (KBN).

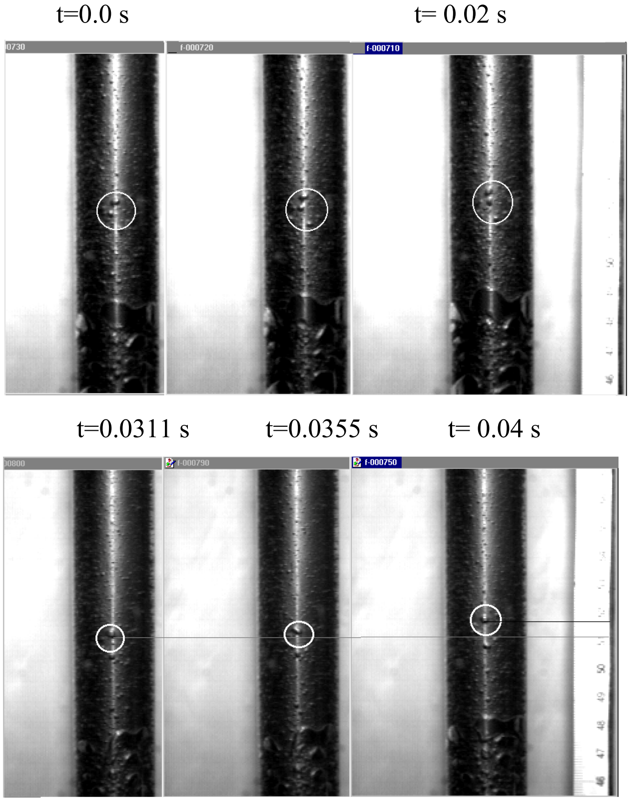

Fig. 1. The vapour bubble movement.

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RESULTS OF Y-89 IRRADIATION ON U/Pb-ASSEMBLY USING 0.7GeV PROTON BEAM FROM THE JINR NUCLOTRON

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The neutron field inside the U/Pb assembly of the JINR Dubna experimental set-up 'Energy plus Transmutation' (EpT) has been for first time determined with the Y-89 activation detectors. In the experiment the 0.7 GeV proton beam impinged on the cylindrical lead target surrounded by uranium blanket shielded by polyethylene container [1,2]. The spallation neutrons were multiplied in process of uranium fission. The neutron field was determined with eleven pure Yttrium 89 (99.9% Y-89) samples placed in specified positions, (given by the radial and axial distance) inside the U/Pb assembly. Neutron capture in Y-89 yields various (n,xnyp), reactions, where 'x' and 'y' are integer numbers. Resulted isotopes are unstable and gamma active. Yttrium seems to be a very good detector because of its simple and well defined isotope composition as well as many possible reaction channels leading to isotopes with suitable half life times, convenient for activation measurement.

After irradiation ($2 \cdot 10^{13}$ protons striking Pb target were collected) the gamma activity of the samples was measured with HPGe spectrometer. Taking into account necessary corrections we have determined isotope production per one gram of sample and per one beam proton at specified positions inside the EpT facility. The axial (Fig. 1) and the radial (Fig. 2) distribution of produced isotopes were determined [5].

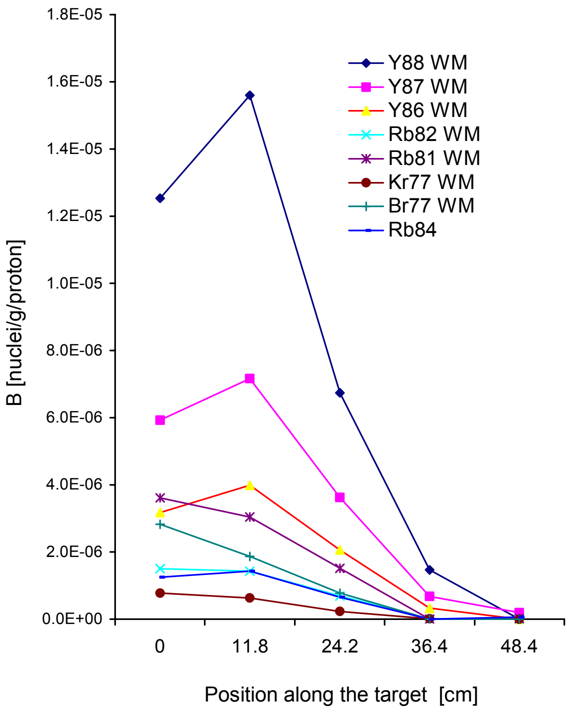

Fig. 1. Axial distribution of isotopes produced at radial distance of 3 cm from the proton beam axis by spallation neutrons in Y89(n, xnyp) reactions.

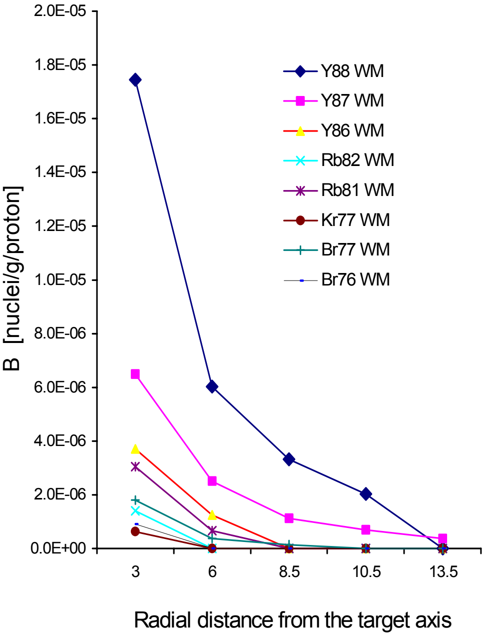

Fig. 2. Radial distribution of isotopes produced by spallation neutrons in Y89(n,xnyp) reactions, at the plane located 11.8 cm from the front.

In the analysis of the axial distribution of isotopes (Fig. 1) is based on the threshold energy for reactions yielding given isotope We found that the lower threshold energy isotopes (Y-88, Y-87, Y-86) attain a maximum of axial distribution in the second plane (between first and second section) 11.8 cm from the front of EpT facility (Fig. 1). This suggests that these isotopes are produced by spallation neutrons created in evaporation process. Higher threshold energy isotopes (Rb-81, Kr-77, Br-77) have maximum in the front plane. Although, higher threshold energy should yield less isotope produced, the production of Rb-81 and Br-77 seems to be exception from this rule.

The radial distribution of produced isotopes (Fig. 2) contains also information about spallation neutron spectrum. However, the detailed evaluation of the spectrum will be a subject of future work.

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ASYMPTOTIC BEHAVIOUR OF AVERAGE PROFILES OF ELECTROMAGNETIC CASCADES IN DENSE AMORPHOUS MATERIALS

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Detailed investigation of both experimental data and results of modelling of electromagnetic cascades (EMC) produced by high-energy gamma quanta in dense amorphous media shows that the commonly used approximation for the average EMC longitudinal profile (ALP) in the form (e.g. [1])

$$(-dE / dt)_{ion} = a_1 x^{a_2} \exp(-a_3 x)$$

is not valid at cascade depths t, where more then 0.9 of the total cascade energy E_γ is released. The variable $x=t/<t(E_\gamma)>$ is the cascade depth t scaled with the average (energy E_γ dependent) depth $<t(E_\gamma)>$ and a_i are free parameters (originally assumed to be independent of E_γ) to be estimated by fitting (1) to experimental or modelled data [2]. Moreover, it turned out that the slope parameter a_3 depends on E_γ as is demonstrated (Fig.1) for the case of EMC initiated in liquid xenon. From the practical viewpoint of special interest is also ALP scaling with gamma quantum energy E_γ, which appears to be broken at large t. Another question of high importance is whether it is possible to recover ALP scaling behaviour by relatively simple modification of the formula similar to the one discussed above.

A similar breakdown of approximation formula was discovered with regard to the average lateral profile of the EMC [3].

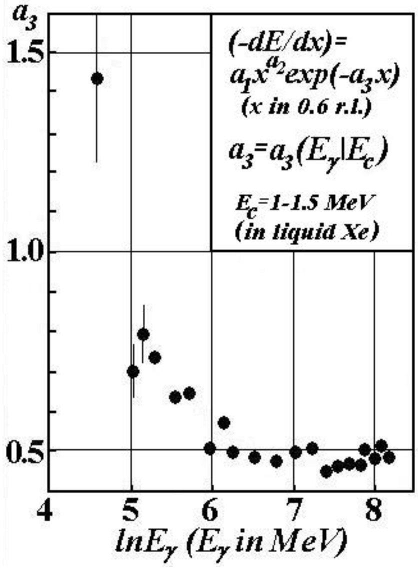

Fig. 1. Energy dependence of the slope parameter a_3 of the fit to average longitudinal profile of EMC produced by gamma quanta in liquid xenon.

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INTRANUCLEAR HADRON-NUCLEI COLLISION SCENARIOS AT SEVERAL GeV AS SEEN BY DIFFERENT MODEL APPROACHES

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It is generally believed that hadrons of energy greater than several hundreds of MeV move in nuclear matter along straight lines between their successive collisions. Such a simple approach is often useful providing at least qualitative insight into many properties and characteristics of nuclear reactions (e.g. [1]). But the matter distribution inside nuclei varies considerably with impact parameter. Moreover, the interactions inside nuclear target differ from those in free state making the intranuclear process much more complicated. At the same time of great interest are many associated problems, in particular, to what extent, if any, admissible is the simplification of this process to an analytic form (like [1]) and what part of the target nucleus is involved in the so-called fast reaction stage, as well as how reliable could be the relation between the multiplicity of different (observed) particles and a degree of centrality of the interaction (expressed by the not observed impact parameter), and the same question with regard to the relation between the particle multiplicity and (pseudo)rapidity distributions. In order to shed light on these problems the investigations of spatial structure of intranuclear processes initiated by several GeV pions and protons have been undertaken. For this purpose two quite different computer programs of simulation of these phenomena were chosen: a typical Monte Carlo cascading code (MC) [2] and an extension of FRITIOF code (FU) [3], based on the dual parton model (e.g. [4]).

The investigation of spatial topography of interaction probability evolution as well as energy and momentum propagation initiated in target nuclei by pions and protons with energy of several GeV has been performed. The subject of the study was also comparison of the dependence of different particles distributions on the impact parameter **b** as calculated with MC and FU code. The simulations have been performed for the inelastic collisions of primary 3.5 GeV/c π^- mesons with Xe nuclei. The results produced with the codes for the lateral dependence of the probability for inelastic collisions caused at head-on impacts (**b**=0) differ significantly (Fig. 1).

The obtained results [5] can provide the basis for simple analytic models like the tube-fireball one which may be very useful providing valuable predictions in many practical problems.

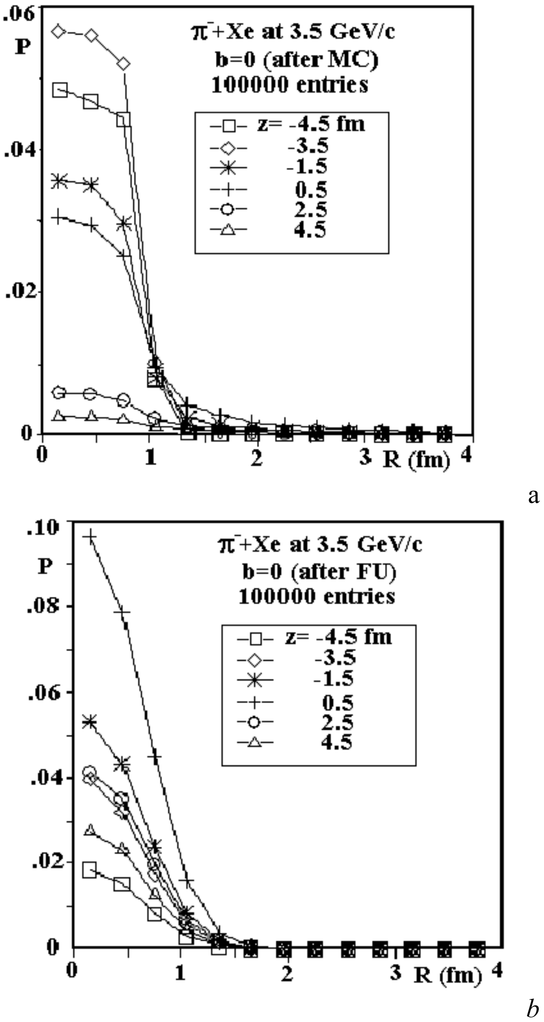

Fig.1. The lateral dependence of the inelastic head on collision probability for 3.5 GeV π mesons with Xe nuclei calculated with MC (a) and FU (b).

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CALCULATION OF NUCLEUS-NUCLEUS MICROSCOPIC OPTICAL POTENTIALS AT INTERMEDIATE ENERGIES

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Three types of nucleus-nucleus optical potentials have been constructed using the microscopically calculated three templates for real and imaginary parts. Two of them V^H and W^H were obtained [1] using the Glauber-Sitenko high-energy approximation theory of scattering (HEA). Another template V^{DF} is calculated as the double-folding microscopic potential with the exchange term included (for example, [2]). For either of the three tested potentials $U_{opt}=N^{(n)}_r\ V^{(n)} + iN^{(m)}_r\ W^{(m)}$ with n,m=H,(DF), the contributions of real and imaginary templates $V^{(n)}$, $W^{(n)}$ are determined by adjusting factors N_r and N_{im}. Calculations for elastic differential cross-sections of $^{16,17}O$ heavy-ions at about hundred MeV/nucleon, scattered on various nuclei, were made in [1,3,4] within the HEA theory. The results are in good agreement with experimental data [5] for scattering of ^{17}O on several target-nuclei (Fig. 1).

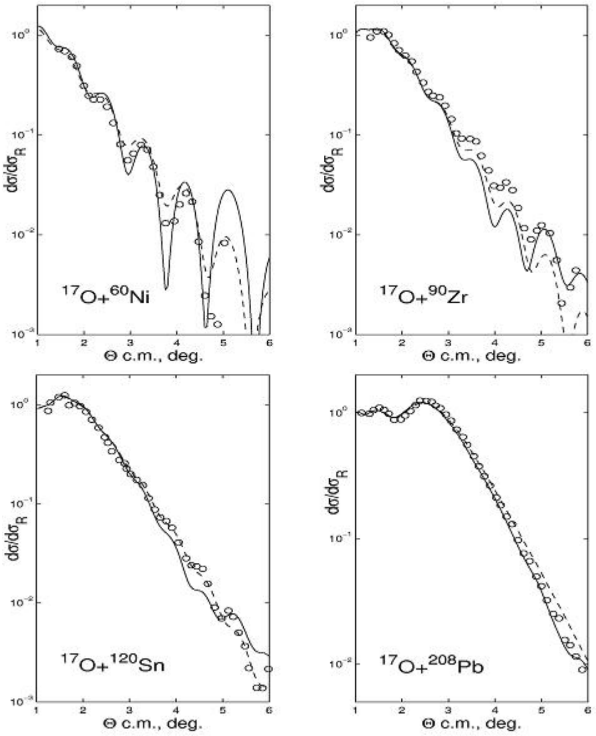

Fig.1. Comparison of the HEA and Schrödinger equation solutions with ECIS code with experimental differentia cross sections for ^{17}O scattering on ^{60}Ni, ^{90}Zr, ^{120}Sn and ^{208}Pb.

The normalization factors for the potentials $N_r\ V^{(DF)} + iN_{im}\ V^{(DF)}$ are as follows: N_r=0.6, N_{im}=0.6 for ^{60}Ni; 0.6, 0.5 for ^{90}Zr; 0.5, 0.5 for ^{120}Sn; 0.5, 0.8 for ^{208}Pb. For comparison the problem was treated by solving the Schrődinger equation with the ECIS code [6]. We conclude that the presented method of constructing the semi-microscopic optical potentials which uses only two free parameters is reasonably effective as compared to the usually applied phenomenological models with 4 and more fitting parameters.

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