NUCLEAR POWER:

THE SECOND ENCOUNTER

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From the Authors

This brochure is a sequel to the "Nuclear power: the first encounter" brochure by L. Dobrzyński and K. Żuchowicz (NCBJ, 2012). Just like the previous one, it has been written generally for persons interested in nuclear power, in particular in development of new types of power reactors. Some elements of the Polish government programme to develop the first nuclear power plant in Poland – including nuclear safety issues – are also presented. In that context we considered useful to describe also reasons and consequences of the most important nuclear accidents that happened in history of commercial nuclear power industry. However, scope of subjects dealt with in this brochure is quite broad, for example some economic aspects of nuclear power have also been tackled.

This brochure (as well as several others devoted to various ionising-radiation-related subjects) may be downloaded from NCBJ webpages, e.g. from http://ncbj.edu.pl/materialy-edukacyjne/materialy-dla-uczniow (majority of the brochures are in Polish). As usual, we have tried to make this brochure as easy to comprehend and absorb as practical, but readers are strongly advised to first read the above mentioned "Nuclear power: the first encounter" brochure. The latter will be referred to many times in this text as "previous brochure" or "the first brochure" and we hope that the context will undoubtedly indicate what is referred to. Lecture of the first brochure is especially recommended to readers not familiar with basics of nuclear power.

Enjoy your reading!

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1. WHAT THIS BROCHURE IS ALL ABOUT?

In the "Nuclear power: the first encounter" brochure[1] we have in detail presented principles of operation of nuclear reactors and typical constructions of power reactors used to produce electricity. We have addressed also nuclear safety issues and tried to answer a number of peoples' main concerns, such as: Are nuclear reactors safe in operation? Is ionizing radiation harmful? What can be done with spent fuel? Is it safe to transport and store such radioactive waste? We have briefly shown how important nuclear power can be for national economy and how nuclear power plants can attract tourists. Additionally, we have tried to outline some perspectives of development of nuclear reactors and related technologies, however the size of the brochure was a very limiting factor.

In this brochure we will try to address the following issues:

- How a decision to build a nuclear facility in Poland is made? As we will see, each potential developer of such a facility must go a thorny path to obtain all relevant permits.
- What passive safety circuits are and what their role is? Safety is the highest priority in every nuclear project. Reactor safety systems are constantly improved, even if the currently used ones are already highly reliable. Although this may not be apparent, this brochure will not offer just a breakdown of used technical solutions, but mainly a breakdown of guiding principles followed by reactor designers and operators.
- How many serious reactor failures have been recorded in the history of commercial nuclear power industry, what were their causes and consequences? Detailed analysis can provide invaluable knowledge what went wrong, and what must be improved to prevent such accidents in the future.
- What is the economy of nuclear power generation?

Before we start let us remind some basic facts. PWR *(Pressurized Water Reactor)* and BWR *(Boiling Water Reactor)* are the two most common types of nuclear reactors used by power industry all over the world. Hot water circulating primary cooling loop in reactors of the former type produces steam in heat exchanger, an element of secondary cooling loop; water in both loops is physically separated. On the other hand, steam is produced directly within cores of the BWR reactors. Even if BWR construction is simpler than PWR one (single cooling loop vs. two separate loops), it is PWR type which currently dominates in majority of nuclear power plants all over the world. Both types are depicted in Figs.1 and 2 copied from the "Nuclear power: the first encounter" brochure.

Each nuclear reactor produces large amounts of ionising radiation/radioactive substances. However, practically all that radiation is absorbed by suitable shields while radioactivity is contained within suitable containments. Amounts of radioactive gases released via a high reactor stack are extremely low. Reactor-originated radiation absorbed by someone living in close vicinity of a normally operated nuclear power plant increases his/her exposition by less than 1% of natural background originating from space, rocks, soil and various radioactive elements built into human bodies (Fig.3). People have been co-existing with background radiation from the dawn of human history. More information on that subject may be found in the "Spotkanie z promieniotwórczością" brochure (in Polish), also available

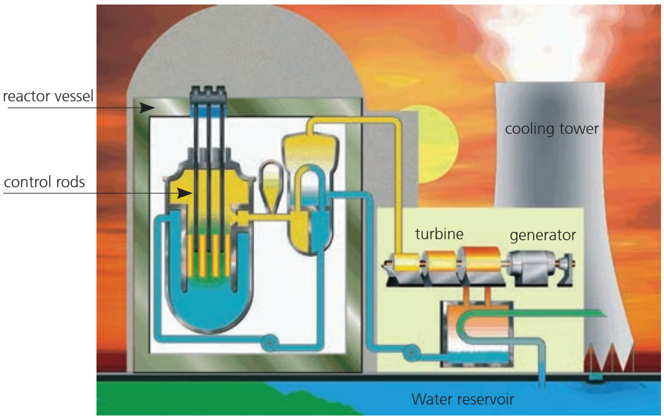

Fig. 1 PWR reactor layout. Hot water leaving reactor vessel produces steam in heat exchanger of the secondary cooling loop. The steam drives the turbine.

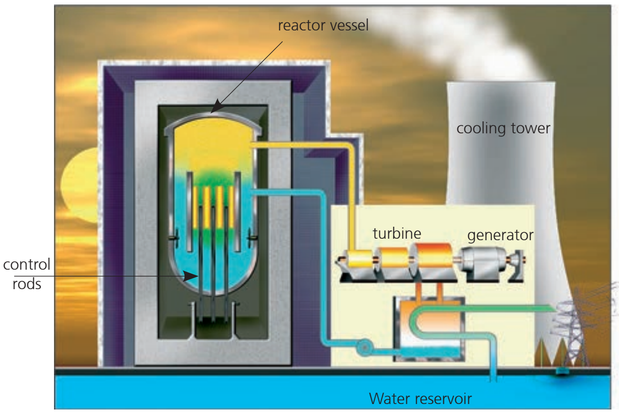

Fig. 2 BWR reactor layout. Steam is directly produced in the upper part of the reactor vessel. All the remaining elements are similar as in PWR reactors, see Fig.1.

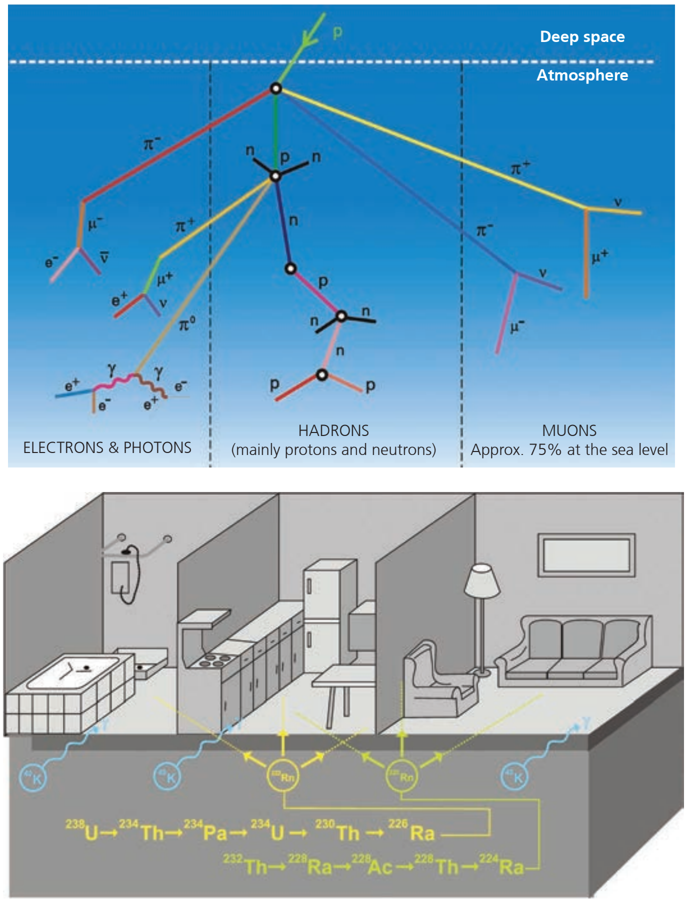

Fig. 3 Background ionising radiation arrives to us from both deep space (top) and Earth crust (bottom). On its way to Earth atmosphere, radon (Rn), an inert (noble) radioactive gas produced in decays of various transuranium isotopes in Earth crust (uranium U, protactinium Pa, actinium Ac, thorium Th) penetrates also our homes. Soil contains radioactive potassium 40.

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[1] L.Dobrzyński, K. Żuchowicz, "Nuclear Power The first ecounter", NCBJ (2015); http://ncbj.edu.pl/materialy-edukacyjne/materialy-dla-uczniow (PDF, 7.1 MB, in Polish)

on NCBJ web pages at the above mentioned address. Typical doses of ionising radiation absorbed in various situations in everyday life (in *milliSieverts*) are shown in Fig.4. Let us now proceed to our objectives formulated above.

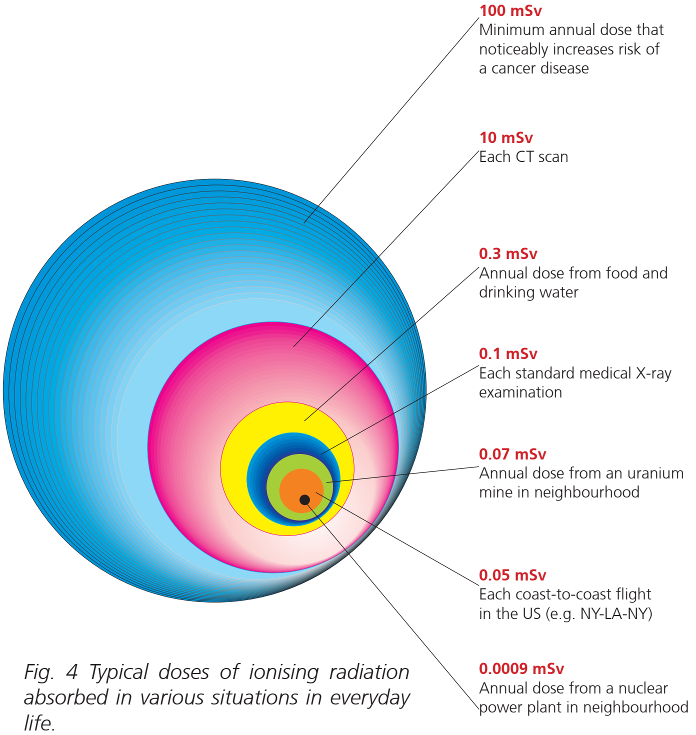

Fig. 4 Typical doses of ionising radiation absorbed in various situations in everyday life.

Should you be not able to find a satisfactory explanation of any of your doubts in the following text or should you feel that some topic has been discussed insufficiently, please feel free to contact us via the www.atom.edu.pl webpage.

2. HOW A DECISION TO BUILD A NUCLEAR POWER PLANT AT ANY GIVEN SITE IS MADE?

Polish government has already made a decision to build the first nuclear power plant in Poland. That political decision was by no means straightforward since economic viability and positive attitude of the Polish society to the project still remains to be demonstrated. However, let us imagine that the investor has been selected, sufficient financing secured, public opinion fully convinced, and it is time to select a place where the plant will be erected and to select one of the available reactor types. Both tasks are not simple to accomplish and such decisions need quite a long time to be knowledgeably made.

The site must meet a number of conditions, which usually are not as easy to meet simultaneously. To verify the conditions are indeed met some tedious hydrogeologic surveys must be done at the site.

Secondly, numerous detailed safety - and usefulness-related solutions are available for each reactor type. The selected reactor safety measures must be in each case approved by an official body having an authority over the investors. In Poland such regulatory oversight is carried out and suitable licenses/permits are issued by National Atomic Energy Agency (PAA). To that end they have to very carefully scrutinize many volumes of reactor blueprints and often ask for help external experts from some Technical Support Organisation (TSO). Multi-step administrative proceedings that must be successfully concluded before investor will be entitled to start any works at the construction site usually take many years to complete. All relevant authorities (both local i.e. county/voivodeship governments and central agencies) are involved in the proceedings.

Safety of nuclear power plants depends on oversight carried out by national regulatory agencies, expertise of the involved TSO organizations (that provide technical and scientific base), and fundamental legal acts formulated in line with recommendations of International Atomic Energy Agency (IEAE Vienna). However, experience from other countries is of limited value here: local elements of the nuclear safety infrastructure must be recreated and operated in each particular country. Let us have a closer look on the key elements.

Fig. 5 Headquarter of International Atomic Energy Agency (IEAE) in Vienna .

2.1 Plant location

It is rather obvious that not every place is fit for a nuclear power plant. The relation is bidirectional: of course hazards brought about to people living nearby must be manageable, but also impact of the environment on the planned plant must be within some limits. Quite a range of factors must be taken into consideration.

The first consideration is safety of nearby inhabitants in case of an emergency. Problems with potential evacuation exclude densely populated areas. A study of population distribution and available access routes must be prepared for any considered area. Depending on worst case hypothetical releases of radioactive substances in emergencies, preliminary evacuation plans are worked out and evaluated.

Site geological conditions are the most essential among external factors that might influence plant operation or even potentially cause an accident. Features analysed to assess the considered site include:

- soil stability (to assess settling of buildings)
- occurrence of tectonic faults
- seismic activity (the strongest earthquake expected in 10 000 years must be identified using archive data and numerical modelling techniques).

Construction costs strongly depend on site seismic activity. The plant may be made quake-resistant, but it may cost a fortune. Fukushima power plant was designed for quakes that can accelerate ground to not more than 5 m/s^2 and indeed survived the quake of just that magnitude that occurred in March 2011. European plants can survive only much milder quakes. Polish law forbids to construct nuclear power plants in places where the strongest quake in 10 000 years might accelerate ground to 1.5 m/s^2 or more.

Site hydrologic conditions, both in terms of potential flooding and potential risk that water needed to cool the plant down will ever be in short supply are equally important. Each nuclear power plant needs for normal operation water from the environment to cool down steam used up in its turbines; warm water its next returned to the environment. The involved volumes are quite significant, on the order of several tens of cubic metres per second per each turbine. Therefore sites located at large rivers/lakes or just at a seashore are preferred. Seashore locations are even better since: (i) sea water is colder than river one and smaller volumes must be pumped; (ii) sea level is more stable even during draughts or floods that may significantly fluctuate river water level. Analysis of site hydrologic conditions takes into account water levels in selected points on major rivers in the country measured over long periods by relevant national agencies. Two important outcomes of such analysis include: (i) map of rainfall water drainage paths (helps to identify places exposed to a risk of flooding), and (ii) map of ground waters and directions of their flow (helps to identify risk of ground water contamination in case of a serious nuclear accident).

Polish law requires that a potential site must be constantly monitored (in terms of meteorological observations, seismic measurements, and geological drilling) for at least two years before an analysis of the site may be concluded with a report.

Human activities within the region where a nuclear plant is considered is another story. Polish law requires to identify various human activities within the region of generally 5 km radius around the site, and 30 km for some specific activities. The to-be collected information include:

- industrial plants located within the region and threats they might pose (explosions, leaks of chemicals etc.)
- operated mines/already shut down excavation voids (risk of seismic earthquakes/ mining damages that could influence soil stability and flow of ground/surface waters)
- identified mineral deposits (that might be mined in the future)
- military objects
- railway lines (that might be used to transport dangerous materials, e.g. fuel)
- airways (air traffic corridors).

The latter issue (air traffic corridors) took on a particular significance after the 9/11 terrorist attack. That attack revealed potential threat posed by large airplanes fully tanked with fuel. That's the reason no nuclear power plant in Poland may be located closer than 10 km from the nearest airport, unless the investor proves that a chance an airplane falls down on plant premises is more rare than once in 10 million years.

Fig. 6 New York, September 11, 2001.

Finally, surveys of all considered sites include also measurements of background radiation levels. If a nuclear power plant is erected at some site, results of measurements made within framework of that site survey will be used as a reference point for radiation levels measured after the plant is put into operation.

Outcomes of all surveys, measurements, and analyses are put together into a single document called Location Report. The report is submitted together with general info on the planned nuclear power plant for approval by PAA President. Having considered the submitted documents, PAA President issues a tentative opinion on the given plant location. A positive opinion is a green light to start works on detailed designs of the planned facility. It is a time-consuming and expensive task to prepare a full-blown Location Report. Therefore usually some superficial analyses of several potential sites are carried out first to select the most promising ones for further studies. Such analyses assigned in 2010 by Polish Ministry of Economy covered 27 potential sites in Poland. Location studies currently (2014) conducted in Poland include only the three most promising sites.

Two concentric zones defined around each nuclear power plant include smaller Restricted Usage Zone and larger Emergency Planning Zone. Some restrictions concerning construction of new housing dwellings are introduced within the former one. Evacuation plans must be worked out and evacuation means must be prepared for all inhabitants of the latter one. Such distinction reflects practical consideration that successful evacuation needs some time; radioactive substances possibly released in case of a serious accident will sooner contaminate some area in the nearest vicinity of the plant. Size of both zones is very closely linked to reactor construction (in particular to tightness of its safety containment) and estimated accident probability. Some reactor suppliers claim that Emergency Planning Zone around their modern reactors could be limited to a few km radius.

The accepted radiuses of emergency zones have serious economic consequences. US regulations call for two zones: 10 mile radius Emergency Planning Zone and 50 mile radius zone, in which crops not yet harvested from fields would have to be destroyed and all food would have to be controlled. In Europe with its larger population density such large emergency zones would make any nuclear power plant practically impossible to locate. However, in view of smaller emergency zones, reactor safety containments must be respectively more reliable (tight), which seriously increases constructions costs.

2.2 Nuclear regulatory agency

Nuclear regulatory agency is a government body which (i) is fully independent of any operator of any nuclear facility operated in the country and of any investor striving to develop such facility; (ii) has an authority to make decisions operators/investors must comply with and an authority to impose sanctions (penalties) on them. International Atomic Energy Agency (Vienna) has suggested that competences of such agencies in respect to nuclear power plants should include:

- analysis of documents submitted by investor applying for approval of a prospective plant site
- evaluation of completeness and correctness of the submitted reactor safety report (i.e. full technical documentation and description of the way the reactor is to be operated)
- supervision of the plant at every stage of its lifecycle (development, construction, operation, shut-down/ decommissioning)
- licensing every stage of plant lifecycle (issuing permits for each essential change).

Analyses conducted by nuclear regulatory agency must be very thorough, so they often take a long time to conclude, e.g. usually two years are needed to proceed an application for a nuclear power plant construction permit. Agency's experts request the applying investor to supply complete design and operational data on which plant safety possibly might depend. They may request the investor to conduct additional analyses or to present additional experimental evidence. They may also conduct their own independent analyses to verify data contained in the reactor safety report.

Nuclear regulatory agency works out safety guidelines/ regulations that must be followed/ complied with by all operators of nuclear facilities. No works on which facility safety might possibly depend cannot be started without suitable permit granted by the agency. Should an operator not follow the guidelines or not comply with the regulations or otherwise breach nuclear safety principles, the agency may impose various sanctions, including an order to suspend the operations. Independence of the agency from any investor/operator is an essential factor improving safety of nuclear power industry.

As was mentioned above, National Atomic Energy Agency (PAA) plays the role of nuclear regulatory agency in Poland.

2.3 Technical Support Organisation (TSO)

The Chernobyl accident (April 26, 1986) has changed a lot in nuclear power industry all over the world. Rate of the industry growth was choked off since social acceptance for construction of new plants dramatically collapsed. Some societies (e.g. Germans) have even demanded to shut down all already operated nuclear power plants and such a decision was indeed made in Germany. After the Fukushima accident (March 11, 2011) it was not an easy task to convince Japanese society to put their nuclear power plants back in operation[2]. Increased efforts to design third-generation much more safe reactors was one of the Chernobyl accident most essential aftermaths (various generations of nuclear reactors are discussed in the next chapter of this brochure). Increased efforts to increase efficiency of the system of supervising nuclear power plants by nuclear regulatory agencies was one of the Fukushima accident most essential aftermaths.

The TSO (technical support organization) idea has boomed after the Chernobyl accident. TSOs have been implemented differently in various countries: their tasks, competences, and formal statuses (empowering levels) are different in various countries. However, each TSO is backed by scientific/technical potential capable to conduct necessary R&D works (including computational infrastructure usually necessary in such projects) and/or to verify not yet checked technical solutions.

In various countries TSO is organized differently. For example, TSO in US is a part of US nuclear regulatory agency, in France and Czech Republic they are external bodies whose mission is to support their nuclear regulatory agencies, in yet other countries TSO services may be hired by both nuclear regulatory agencies and by nuclear industry. However, in every case a complete independence of TSO experts is the utmost issue. Great care is taken that their opinions might be formulated in an atmosphere free of any conflict of interests. For example, employment of any TSO staff member by any of the two other members of the investor-nuclear regulatory agency-reactor/plant supplier trio is excluded.

2.4 Reactor licences and certificates

The above described proceedings are aimed to get a *licence* to operate nuclear reactor. Every prospective nuclear reactor operator must apply for such a licence to nuclear regulatory agency in the given country. Reactor *certificate* is quite a different thing: it is an official statement that the given reactor model meets all safety requirements in force in the given country. Not every country requires reactor *certificates*.

Licensing proceedings are compound processes depicted in Fig.7[3]. Investor must apply to nuclear regulatory agency for a permit to construct nuclear power plant. Both Investor and the agency may use services of some TSO (several TSOs may render their services in the country). To be able to formulate knowledgeable opinions, a TSO must have suitable technical & scientific base. Investor may assign some TSO a task to formulate an opinion on a design supplied by some prospective supplier.

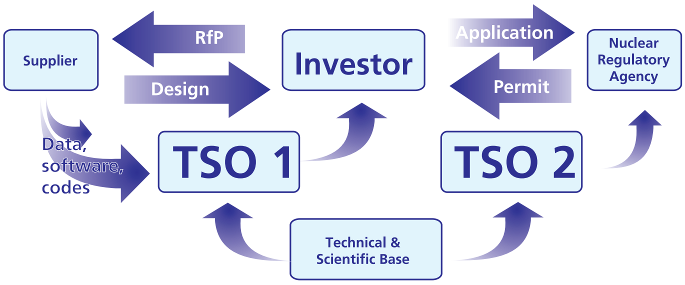

Fig. 7 Institutions involved in nuclear power plant licensing (RfP = Request for Proposal).

2.5 Social attitude

It is rather obvious that society should be able to influence decisions that might significantly impact social life in a long period of time. However, to be able to knowledgeably speak up on nuclear power issues, society must understand the balance between risks and benefits brought about by the technology. Without prior education based on information from trustworthy sources what the consequences of developing a plant on any given site might be and what the consequences of NOT developing that plant might be, any form of social participation in decision making (e.g. a referendum) may be unreasonable. Therefore a programme to educate the society as much as possible should be implemented before the final decision is made. Taking into account specifics of scientific research, it is also in the best interest of the society to foster research in the nuclear field. A number of issues related to that latter topic have been addressed in our previous brochure.

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[2] Nevertheless, Japan government made in 2014 a decision to put some of their power reactors back in operation.
[3] A slide from presentation by Prof. G.Wrochna, Director General of National Centre for Nuclear Research (2013)

2.6 International collaboration in improving nuclear safety

Awareness that nuclear accident in any one country may have global consequences and influence nuclear power industry all over the world has been profoundly impacting nuclear safety standards. Therefore all involved parties are willing to internationally collaborate and to help each other in improving the standards. Know-how collected when fighting consequences of a nuclear accident in one country is shared among all other interested countries. Achievements of the best power plants are propagated as "good practices" and may be free-of-charge implemented in other plants. Such global-scale learning process is very effective in implementing the best practices to all plants employing reactors of the given (or similar) type, provided that it is not hampered on some political grounds.

International Atomic Energy Agency (Vienna) has comprehensively analysed construction of WWER and RBMK reactors manufactured in the former Soviet Union. WWER belongs to the PWR family of reactors, while uniquely designed RBMK reactors were used only in Soviet Union, including the Chernobyl power plant. A separate "green book" of all weak points, potential threats and guidelines how to remove/avoid the threats was worked out for each of the two reactor types. The books are major reference materials for IAEA inspectors who help to evaluate current safety of power plants in which such reactors are still operated and suggest how that safety might be improved. The books are also used by nuclear regulatory agencies all over the world. Recently IAEA has worked out also similar green books regarding PWR reactors designed in Western countries. Extensive programmes of know-how exchange are run by World Association of Nuclear Operators, an organization with interests vested in safety of operation of nuclear power plants. Also, several programmes of direct cooperation between power plants of similar types operated in various countries and government-level programmes of bilateral cooperation between countries less- and more-advanced in technology are run. All that have resulted in a quick flow of information and have taken care of effective implementation of improvements in nuclear power plants operated in various countries.

In this context let us point out that some extra risk may be associated with nuclear power plants: (i) located in countries socially/politically unstable and/or otherwise unable to make use of wealth of nuclear safety know-how accumulated throughout the world, or (ii) developing their own reactor constructions different than typical constructions commonly used all over the world.

3. REACTOR GENERATIONS

Constructions of nuclear reactors are by convention classified into a few "generations", usually as follows.

First commercial reactors built in 50' and 60' of the 20th century were making up the first generation. Examples include Magnox reactors built in the UK, and the first PWR and BWR reactors built in the US. That early generation was however composed of a real multitude of types and models, out of which majority turned out unsatisfactory and were eventually abandoned (reactors with organic moderators, graphite-sodium reactors to name a few). On the other hand, the Calder Hall plant operated in UK between 1956 and 2001 is an example of a very successful 1st generation construction. Single reactor/power generation unit of those times could deliver 50-200 MWe[4].

Second generation reactors appeared in the decade of 70'. Till that time the multitude of the 1st generation gave way to just a few constructions: PWR (and WWER Soviet counter-part)[5], BWR[6], PHWR[7] a.k.a. CANDU[8], RBMK[9], and AGR[10]. 2nd generation reactors are still being built in some countries, in particular in China. Power of a single reactor/power generation unit can reach 1 300 MWe, however typical range is 900 -1 100 MWe.

Failure of the Three Mile Island plant (1979, see section 7.3 below) was an event that ended the era of 2nd generation reactors. The lesson learnt on that occasion motivated nuclear agencies in many countries to toughen up the regulations. The major new requirement was that 3rd generation reactors would have to have much lower probability of serious accidents, while buildings in which they are situated would have to be specially designed to cope with such emergencies. It is not an easy task to meet such criteria. In the era of 3rd generation reactors the number of technology suppliers has dropped down to just a few in the world, while reactor/power plant costs have soared. Some manufacturers claim their reactors belong to 3+ (III+) generation, but criteria accepted in the US and in Europe to be classified as 3+ are different and the whole thing seems to be a marketing catch. 3rd generation reactor-based nuclear power plants are currently under construction in several various places in the world. Besides, a few ABWR[11] boiling water reactors classified also to 3rd generation have been operated in Japan for several years.

All future technologies are rated as 4th generation. Reactors of that generation will be constructed using radically different technologies and radically different approach to safety issues. No reactor of that generation is so far (2015) operational. List of expected improvements is quite long:

- radically decreased amount of produced nuclear waste
- at least partially closed fuel cycle (waste recycling)
- power generation efficiency 45-50% (currently about 35%)
- no fission material produced within the reactor core may have any military application
- increased safety level.

Fig.8 shows time evolution of reactor generations. In each subsequent generation safety is better than in the previous one. Technical solutions that have not proved their merits in practice are eliminated.

Majority of reactors operated these days belong to the second generation, while majority of reactors under construction – to the third generation.

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[4] MWe = megawatt of electrical power
[5] PWR = Pressurized Water Reactor, WWER = Water-Water Power Reactor in Russian
[6] BWR = Boiling Water Reactor
[7] PHWR = Pressurized Heavy Water Reactor
[8] CANDU = Canadian Uranium Reactor
[9] RBMK = Large Power Channel Reactor in Russian
[10] AGR = Advanced Gas Reactor
[11] ABWR = Advanced Boiling Water Reactor

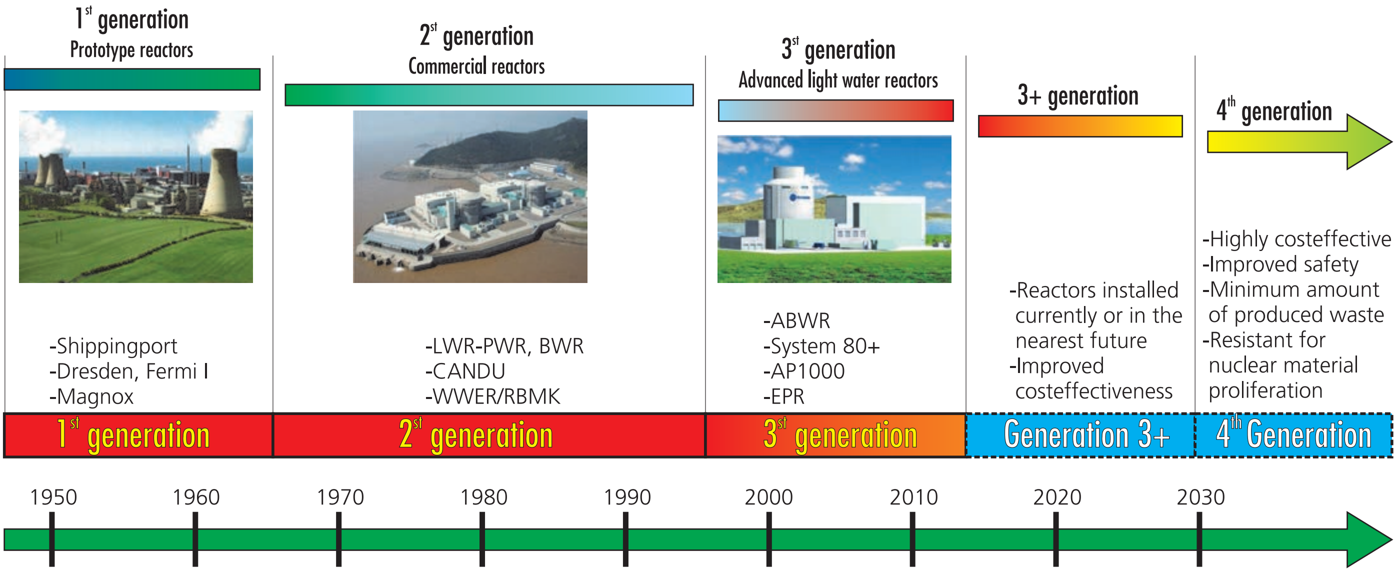

Fig. 8 Time evolution of reactor generations.

4. PASSIVE ELEMENTS OF REACTOR SAFETY SYSTEMS

As a very important subject, nuclear reactor safety needs a separate presentation. We have already said in the previous brochure that reactor safety is based on multitude of barriers. We meant constructional elements which prevent the situation in which fission products might be released outside the reactor room. Let us remind the four major barriers:

- fuel element construction (it directly entraps uranium fission products)
- fuel element cladding
- walls of steel elements (reactor vessel, pressure stabilizer, cooling loop tubing, heat exchanger etc.)
- reactor safety containment.

In this chapter we are going to put emphasis on an essential feature of reactor safety systems, namely their passivity. Passive systems are driven by simple physical forces (such as gravitation or convection) even in absence of external power and without operator intervention.

The first action during each reactor start-up is to pull emergency rods up and to drive them outside the reactor core. The rods are hanged under some electromagnets.

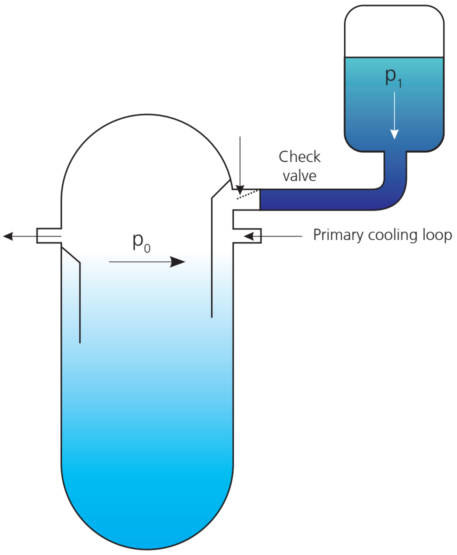

Fig. 9 Check valve-based passive core flooding system.

In case of any blackout of electric power in electromagnet coils, attractive forces of electromagnets disappear, the rods gravitationally fall down on their places between fuel rods and automatically extinguish the chain reaction. Gravitation is passive element of the safety system.

The most deadly failure of any nuclear reactor is loss of cooling, since in absence of cooling reactor core may melt down. Reactors must be ready for such failures. Typical solution is to pump emergency cooling water from a system of multiple emergency reservoirs (so-called accumulators or hydro-accumulators). Normally the pumps need electric power. However, the problem may be approached differently. Hydro-accumulators may be located in the vicinity and above the reactor core and be connected with the reactor vessel by a short tubing equipped with a check valve. During normal plant operation compressed nitrogen pumped to the reactor vessel maintains pressure p_0 inside the vessel higher than pressure p_1 exerted on the check valve by mass of water in the hydro-accumulator, so the valve is closed. However, as soon as the p_0 pressure drops, the valve opens enabling the water to flood the core until p_1 drops below the check valve threshold. This is typical passive element of the safety system. Safety depends on static pressure difference, core flooding is triggered without any operator intervention and may proceed without any external power source.

Of course no hydro-accumulator is inexhaustible. Nevertheless, hydro-accumulator may give some time to start up other (active) systems capable to take over the core cooling function before core melts down should the primary loop be broken.

Another example of passive safety element is shown in Fig.10. Circulation of water (hence cooling) is guaranteed (even in absence of power in pumps) by different density of hot water inside reactor vessel and colder water inside external tank with heat exchanger (depicted IC POOL in the Figure) i.e. by convection. In emergencies valve on hot water pipeline to the pumps (depicted ⋈) is closed and heat generated inside reactor core is carried away by water driven by convection forces to a heat exchanger situated above the core.

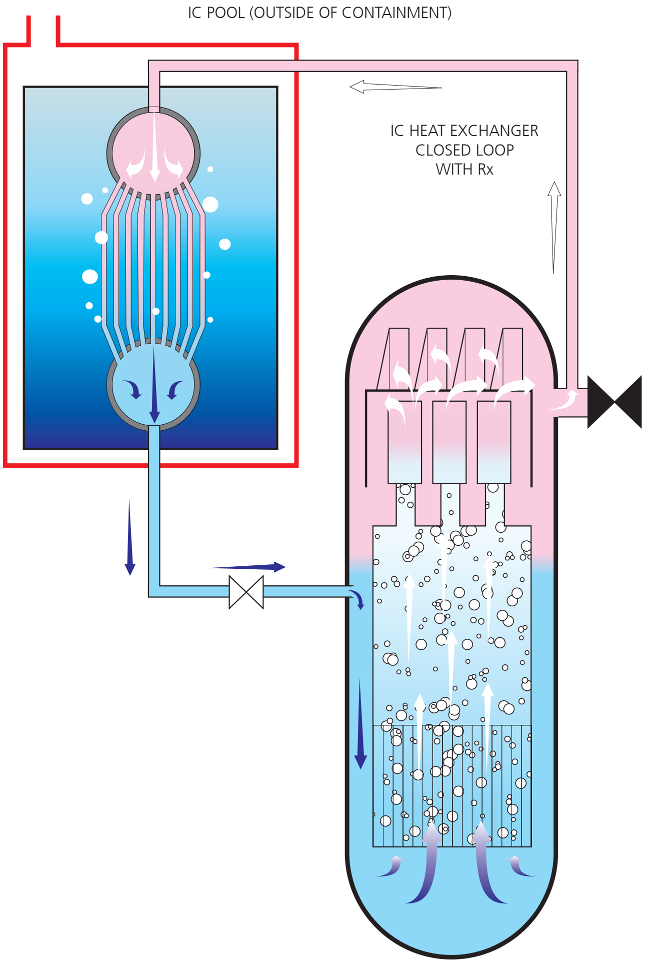

Fig. 10 ESBWR reactor passive safety. (Source: GEH promotional materials).

Electric power should be supplied to pumps even in emergencies by Diesel generators, but in Fukushima the generators were flooded/their fuel tanks were flushed to the ocean by the tsunami wave, and the reactors did lose their cooling. In some systems the power in emergencies may be generated by burning gaseous hydrogen produced inside overheated reactor core in reactions between very hot steam and zirconium present in cladding of fuel elements.

PIUS (Process Inherent Ultimate Safety) concept is shown in Fig. 11. The reactor is immersed in an external pool filled up with solution of boric acid in water. The solution does not mix with the cooling water unless the core becomes overheated in result of some emergency. In such situation the solution is automatically introduced to the core. Water cools the core down, while boron atoms (which strongly absorb neutrons) stop the chain reaction. No reactor was ever built according to that concept.

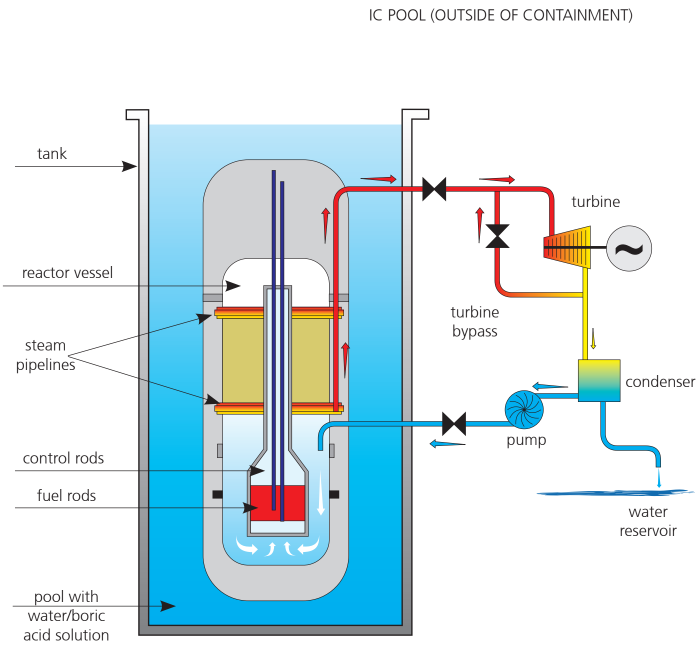

Fig. 11 The PIUS concept (after Wikipedia Commons).

Finally let us mention a simple solution designed to eliminate overpressure in emergencies: a cooling tower. It's role is similar to the role of safety containment. Such a cooling tower was designed for the never built Żarnowiec nuclear power plant. In emergencies steam pressure may suddenly soar; such overpressure would be however quickly eliminated because overheated steam would pass through a series of special water tanks stacked into a tower. Passing through cold water steam would condense, hence its pressure would drop.

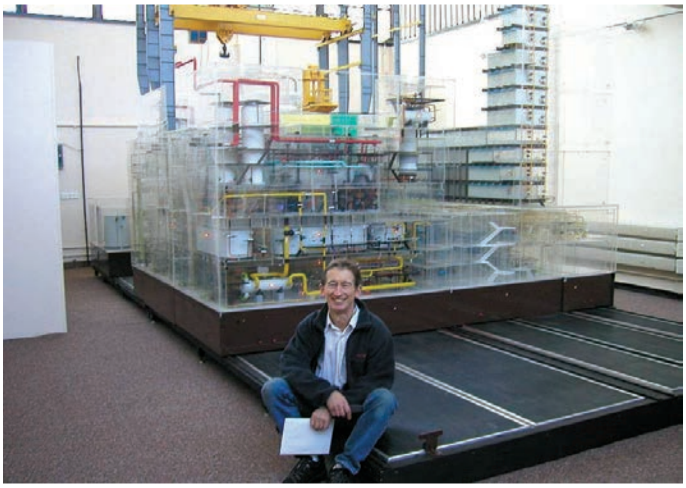

Fig. 12 Model of the never built Żarnowiec nuclear power plant. The plant was to be the first nuclear power plant ever built in Poland, however the project was abandoned in 1990. The model is now exhibited in NCBJ Świerk. Cooling tower visible to the right was to protect the plant against sudden increase of steam pressure in emergencies. In the foreground: Mr. Tadeusz Sworobowicz, one of the technicians working at reconstruction of the model.

5. WHAT IF PASSIVE ELEMENTS CANNOT BE BUILT-IN?

5.1 Redundancy and diversity

Passive elements may not be the only elements of the reactor safety system, some active elements are also necessary. Generally, redundancy and diversity are the two governing principles according to which each safety system is designed. Fig.13 shows an example illustrating the redundancy idea: even if two valves (depicted red in the Figure) fail in the opened position, the third operational one (depicted green) effectively cuts the pipeline off.

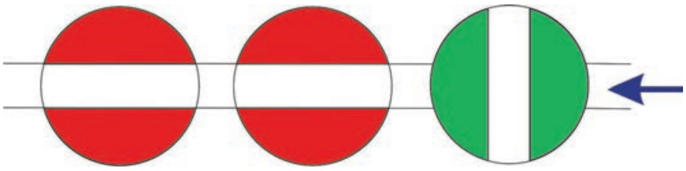

Fig. 13 Example illustrating the redundancy idea: even if two (red) valves fail in the opened position, the third operational one (green) effectively cuts the pipeline off.

Active circuits in safety system are usually paired to mutually back themselves up: should one fail, the other will take over. For example, three separate water tanks each with its electrically driven pump are situated next to every WWER reactor even if during normal operation cooling water might be supplied to the reactor pool from just one such tank. Also high- and low-pressure tanks of the emergency cooling system are tripled. In some state-of-the-art power plants, emergency reactor cooling systems contain as much as four redundant sub-systems, each capable to cool the reactor down on its own.

Control circuitry is redundant, too. Suppose that reactor should be shut down as soon as some pressure have exceeded some threshold value (alarm signal). Let us discuss the situation when the pressure is measured by 1, 2 or 3 gauges:

- 1 gauge: there is some risk that the gauge may fail and either (i) do not trigger the alarm when it should do so, or (ii) trigger a false alarm when there is no reason to do so
- 2 gauges, signal from either of them is enough to trigger the alarm. The risk than both gauges simultaneously fail and do not trigger the alarm when they should do so is much less. However, the risk that one of the gauges fails and triggers the alarm when there is no reason to do so will not decrease – on the contrary, it will be even higher
- 3 gauges, simultaneous signals from two of them are necessary to trigger the alarm. Failure of any one of the gauges will not have any negative consequences; false signals will just signal that the gauge failed and should be fixed

Using redundant circuits one can minimize the risk of events that might pose a threat to the reactor. A significant complication of the circuitry and consequently its higher investment/maintenance cost is the price to pay. On the other hand redundancy gives an opportunity to turn some circuits off for maintenance without shutting the operated reactor off. It is a normal practice especially in relation to emergency Diesel generators, which usually require plenty of time for maintenance.

Diversity should be another major feature of the reactor safety. Diversity means that a few various sub-systems are used to accomplish the same task. Redundancy protects against consequences of single failures of individual elements (valves, gauges etc.) of which the given system is composed, but is not any protection against failure of the entire system because of some common reason unknown to the designers or considered by them a too improbable circumstance. Diversity of the applied elements/technologies/solutions decreases a chance that any common reason would simultaneously inactivate them. For example, two emergency cooling system pumps might be driven electrically, but two others – by a steam turbine. Control rods are usually backed up by quite different system that in emergencies injects boric acid to the cooling water (boron nuclei strongly absorb neutrons and can stop the chain reaction). The latter example illustrates well both the back-up idea and the diversity idea.

Besides, safety sub-systems are *spatially-separated* to avoid loss of more than one sub-system in case of a localized problem (for example a limited area fire). In modern EPR reactors each of the four redundant sub-systems of the reactor safety system is located in another part of the reactor building, far from others. Even an airplane hit would not destroy more than a single sub-system. Analogous rules are observed for cabling: safety circuitry cables are routed separately from other cables, safety system cables and power cables are laid down in separate trays.

Apart redundancy, diversity, and spatial separation, all elements of safety system must be resistant to shocks, and capable to operate in an extremely wide temperature/ pressure/ humidity range. Fire protection plans in nuclear power plants are especially detailed, consequences of flooding individual safety circuitry are clearly identified.

Resistance to earthquakes of systems responsible for reactor shut down/cool down is designed taking into account the strongest earthquake ever noted in the plant area, or estimated numerically at a probability level once in 10 thousand years.

Safety system elements/devices/pieces of equipment are qualified in a time-consuming, costly procedure to be sure they will not fail in emergencies. The tested factors include: aging, vibrations, temperature fluctuations, irradiation and exposition to some chemical substances that might be encountered during plant operation.

5.2 Simpler construction – less things that can fail

Safety system element redundancy generates additional costs not only during plant construction, but also during plant operation. Time necessary for maintenance is a more critical parameter than cost of inspection: plant must be shut down for maintenance of majority of its systems i.e. may not make any money. For that reason reactor designers are working all the time to improve their constructions by shortening the installed system service time. Number of pipelines, valves etc. is reduced as far as possible without giving up system functionality. Area occupied by all plant buildings is diminished. In short, simplicity is squeezing out complexity/complicated functionality that increase risk of failures and/or human errors.

For further discussions of reactor construction evolution let us remind layout of a typical (conventional) PWR reactor. Fig.14 has been copied from the first brochure. The layout shown in Fig. 14 will be our reference point.

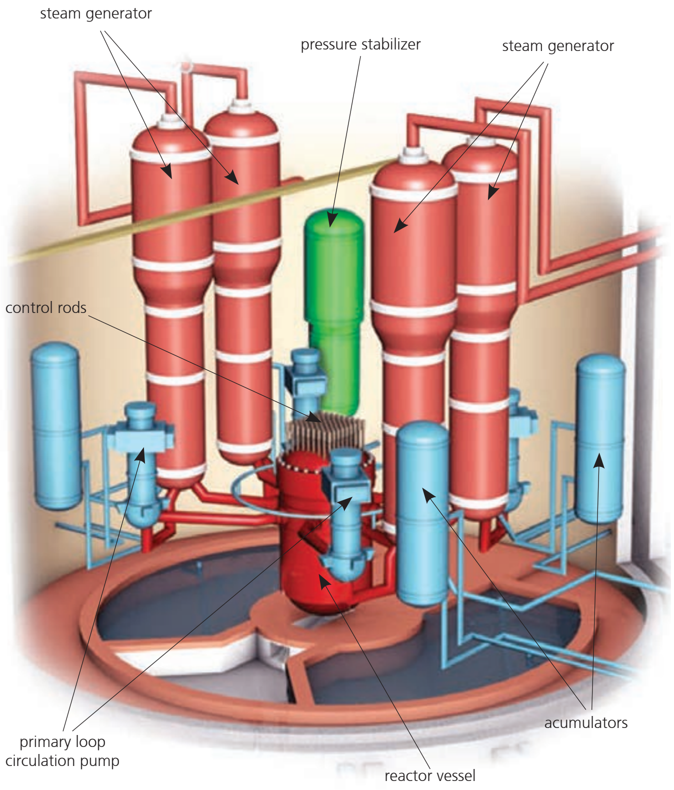

Fig. 14 Typical construction of a PWR reactor: reactor vessel, 4 cooling loops with their pumps/ steam generators, pressure stabilizer. Typical dimensions of the steam generator: height 24 m, diameter 5.2 m, total weight 500 t. Typical dimensions of the pressure stabilizer: height 11 m, diameter 2 m, total weight 146 t. Typical dimensions of the reactor vessel: height 13 m, diameter 5.5 m, total weight 525 t.

5.2.1 Evolution of solutions used in BWR reactors

BWR reactors are good examples of how improvements may be gradually introduced in subsequent versions. In particular water circulation system was improved that way. Early solution is shown in Fig.15.

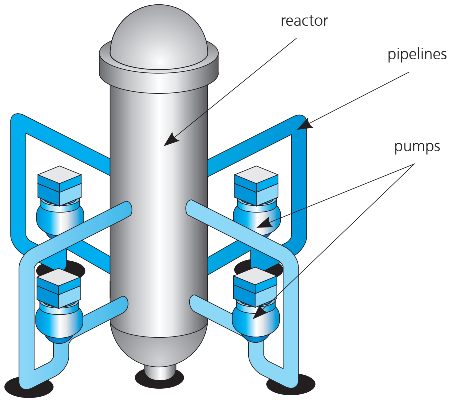

Fig. 15 Circulation pumps and pipelines in one of the early versions of BWR reactors.

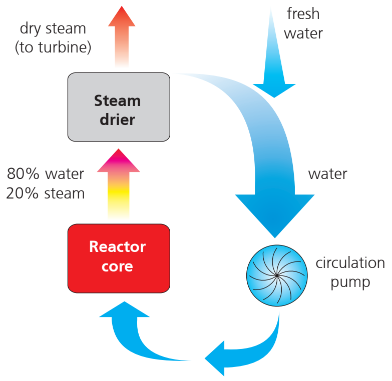

Fig. 16 Water circulation in a typical BWR reactor.

Water flowing between fuel rods of a BWR reactor gradually evaporates on its way from reactor vessel bottom upwards. In no case the water may be allowed to evaporate completely, since a too dry water/steam mixture would not be able to take away all heat generated in fuel rods and in effects the rods would overheat. Therefore usually only about 20% of water introduced into the core evaporates. Steam separated from the mixture in a steam drier is directed to turbine, while water is re-directed back to the core (after supplementing the evaporated 20% with fresh water), see Fig.16.

Circulation pump location must be carefully selected. Pump motor must be accessible from outside the reactor vessel. For that reason in earlier versions of BWR reactors external pumps were connected via some pipelines at the reactor vessel bottom (see Fig.15). However, such solution has a tremendous disadvantage: if one of the pipeline breaks, it is very difficult to keep reactor core immersed since any water pumped into the vessel is immediately drained by the break. Emergency core flooding systems had to be extremely efficient.

That problem was partly solved by the so-called ejectors introduced in next generation BWR reactors, see Fig.17. Circulation pumps are here still external but may be less efficient. That innovation helped to significantly reduce: (i) diameter of pipelines entering bottom part of the reactor vessel; (ii) efficiency of emergency core flooding systems; and (iii) number of motors driving the circulation pumps.

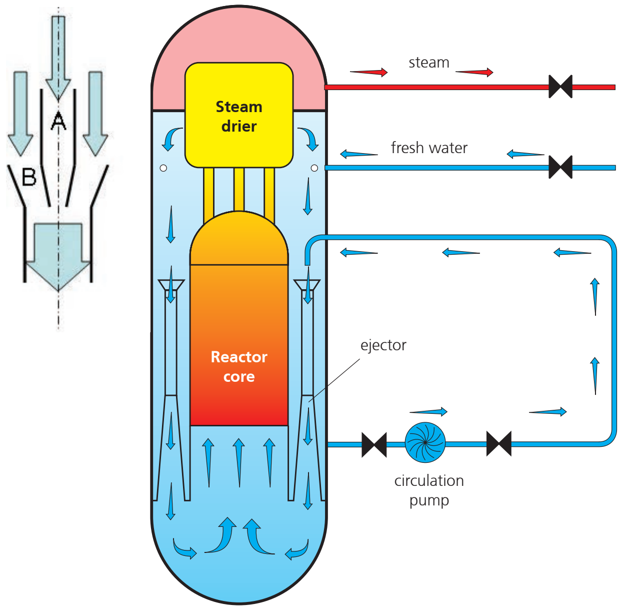

Fig. 17 BWR reactor with ejectors. Relatively small amount of water flowing through nozzle A entrains much more water through surrounding circular channel B. Ejectors help to signifycantly reduce diameter of pipelines connecting circulation pumps.

Another innovation was introduced by Swedish and German designers. Pump rotors have been moved inside the reactor vessel, while pump motors remained external in relation to the vessel. The innovation made possible to completely eliminate pipelines routed outside the vessel. Yet another step was made in Advanced Boiling Water Reactor (ABWR, see Fig.18): pump motors are adapted here to work immersed in water (“wet” motors). The solution allowed to eliminate not only pipelines, but also sealing of the shaft transmitting the drive from the pump motor to the pump rotor; the sealing was very troublesome to maintain.

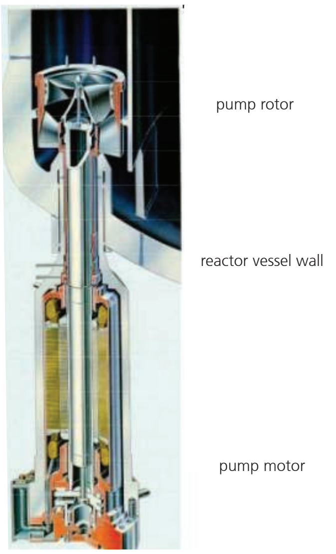

Fig. 18 Circulation pumps in ABWR reactors (source: Toshiba promotional materials).

The most modern solution has been applied in state-of-the-art Economic Simplified Boiling Water Reactor (ESBWR) offered by the General Electric/Hitachi consortium. There are no circulation pumps whatsoever, water in that reactor circulates naturally by convection forces only. Height of the reactor vessel had to be increased to obtain sufficiently strong convection forces. Besides, a new control system had to be worked out since in conventional BWR reactors power control was augmented by controlling flow through circulation pumps.

5.2.2 Evolution of solutions used in PWR reactors

Number of valves, pumps, cables and other equipment necessary to run power reactor was significantly reduced also in some PWR constructions. Reactor building size was also decreased, which means it is easier to build a suitably earthquake-resistant structure. Progress was possible mainly due to a wide application of passive safety elements and automation technology advancements. The obtained progress is illustrated in Fig.19.

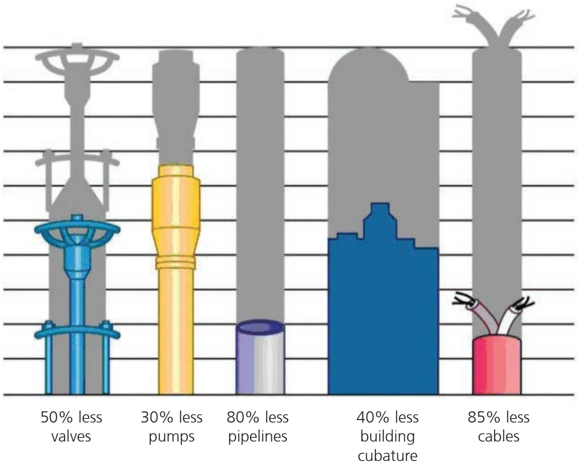

Fig. 19 Illustration of progress in simplifying PWR reactors. State-of-the-art AP1000 construction is compared with typical Westinghouse reactors manufactured in 70' (source: Westinghouse promotional materials).

5.3 Safety containment

No safety system can with 100% certainty exclude possibility of serious accidents. Therefore each power nuclear reactor and its closest equipment is placed inside (surrounded by) the so-called safety containment. This structure's function is to prevent proliferation of fission products which might be released from the reactor core/primary cooling loop in case of a serious accident. In emergencies safety containment is filled up with hot steam, therefore it must be capable to withstand significant pressures exerted from inside (usually at least a few atmospheres).

Suitably large steel tank would be the simplest safety containment. Spherical shape allows to obtain relatively largest strength, so spherical safety containments were indeed used in early constructions, see Fig.20.

Fig. 20 Big Rock Point nuclear power plant in the US. Safety containment in the form of a large steel sphere was typical for early constructions.

Contemporary safety containments must also serve another function: to protect the reactor against external threats, in particular against deadly consequences of airplane strikes. Various countries have introduced different regulations in that respect. Polish regulations require that safety containments be able to effectively protect reactor against strike of a big airliner. Therefore contemporary safety containments are usually made of concrete prestressed with some steel cables. Containments often are made as two-layer structures: function of the inner layer is to withstand pressure of hot steam, function of the outer layer is to protect the reactor against external threats (see Fig.21).

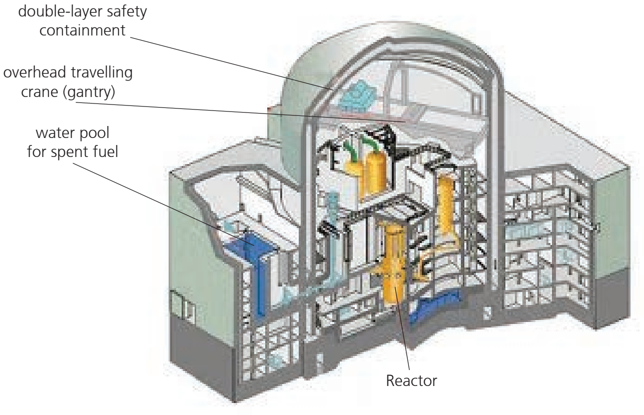

Fig. 21 Contemporary EPR reactor cross-section. Double wall structure with a dome is a two-layer reactor safety containment (source: Framatome).

BWR safety containments are different than PWR safety containments and operate according to a slightly different principle. Since safety containment cost is an essential component of total investment costs, safety containment should be as small as possible. Designers have managed to limit the dimensions using some solutions capable to reduce internal overpressure in emergencies. To that end they have split the containment into two parts, drywell and *wetwell*, see Fig.22. The former houses the reactor and its equipment, the latter contains quite large amount of water. In emergency steam is directed from drywell under water surface in *wetwell*, where it condenses. Thanks to the condensation pressure inside the containment may remain relatively low. Water stored in *wetwell* may also be used to cool the reactor down or to sprinkle interior of the safety containment.

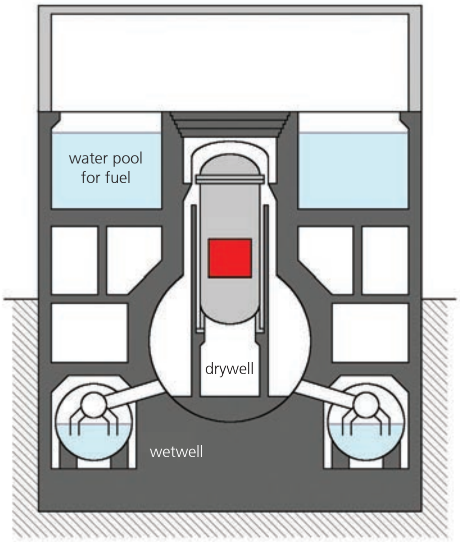

Fig. 22 Mark-I safety containment. Containments of that kind are used in majority of BWR reactors. Similar containment was also used in Fukushima.

As evidenced by the Fukushima accident, the *wetwell* water may not suffice: condensing steam constantly heats the water, and as soon as water temperature reaches boiling point, condensation ceases and the pressure starts to rise. Therefore crucial safety requirement is to keep cooling loops operational. No hot reactor (including "dry" PWR reactors) can survive break in operation of its cooling loop lasting more than several hours.

ESBWR reactor safety containment is much smaller due to yet another solution. Heat exchanger immersed in a large water pool located at upper floor of the reactor building are connected with safety containment. In emergencies steam from the containment is directed to the exchangers where it condenses. Of course water in the pool will gradually become more and more hot and will evaporate, but it could be relatively easily replenished using an ordinary fire truck.

A slightly different solution was used at two PWR reactors installed in the Loviisa (Fin-land) power plant and a few other PWR reactors: a number of baskets for ice and refrige-rating coils of capacity sufficient to produce required amounts of ice have been installed inside safety containment.

A number of redundant systems must be installed to get sufficient reliability of cooling loops. Another approach has been used in the most modern AP1000 (Westinghouse) construction: safety containment is built into a cooling stack with airflow sufficient to condense steam, therefore heat can be passively dissipated to the environment (see Fig.23). Such solution may remain operational in emergencies indefinitely. Additionally, for the first 72 hours after an accident (when heat emitted from the shutdown reactor is most intense) housing walls will be sprinkled with water from the tank installed at the housing top (to improve heat transfer).

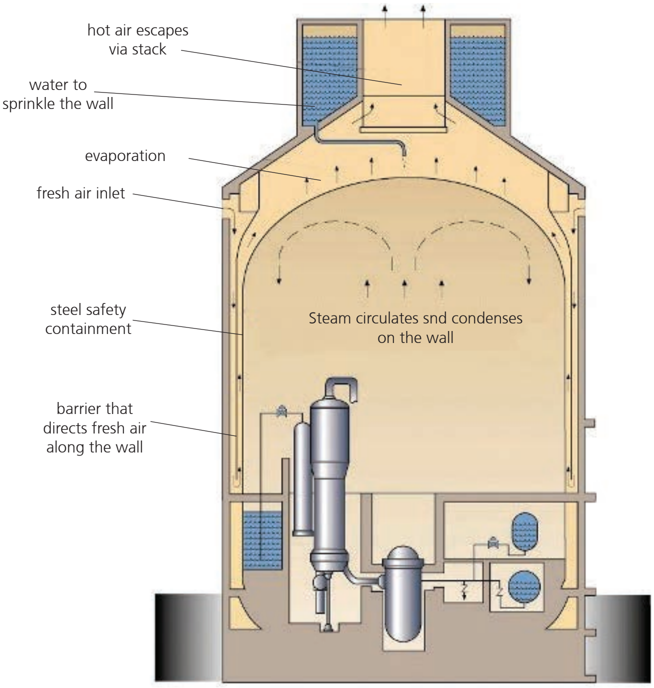

Fig. 23 AP100 reactor safety containment is cooled down passively (source: Westinghouse promotional materials).

Sprinklers usually installed inside safety containment are to help condense steam in emergencies and that way to lower the pressure inside the containment. Besides, sprinkled water helps to rinse soluble radioactive isotopes out of air inside the containment (mainly iodine and caesium).

One more threat that safety containment must cope with is free hydrogen produced in serious accidents in overheated reactor core in reactions between very hot steam and zirconium present in cladding of fuel elements:

$$\mathbf{Zr + 2H_2O \rightarrow ZrO_2 + 2H^2\uparrow}$$

Two devices are used to eliminate risk of hydrogen explosion: igniters (active devices that burn hydrogen before its concentration reaches explosion level) or catalytic re-combiners (preferred since they need no power). Solutions used in BWR reactors are different than those used in PWR ones. BWR safety containments are much smaller than PWR ones, so hydrogen concentration in them rises much faster. Therefore before BWR reactor start up, its safety containment is usually filled up with gaseous nitrogen. However, it can only delay the hydrogen explosion problem: the accumulated hydrogen sooner or later must be released to the atmosphere where it can burn. Fukushima accident was to a great extent compounded just by hydrogen, which was not in time released to the plant stack (most probably operators were not able to do so), and exploded as soon as safety containment finally lost its tightness letting to get sufficiently concentrated hydrogen in touch with oxygen in the air.

6. WHAT IF REACTOR SAFETY SYSTEM FAILS?

Consequences of a serious accident in a nuclear plant may be serious for both plant personnel and local residents. Let us look more closely on that problem.

If significant quantities of radioactive substances are released in result of a nuclear accident, a rescue action must be undertaken. Polish Atomic Law identifies a respective Voievode (country region Governor)/Minister of Internal Affairs as commander-in-chief of a limited-area/wide-area rescue action, respectively. Actions possibly ordered by the commanding officers to prevent loss of life and/or health may include:

- Temporary evacuation of residents. Such action may be ordered if it will reduce dose absorbed by each evacuated person by 100 mSv within the coming 7 days[12].
- Order to stay indoor (10 mSv/2 days)
- Temporary resettlement (30 mSv/30 days).
- Permanent resettlement (1000 mSv/50 years).

The above actions should be undertaken sufficiently prior to irradiation. Therefore the most probable course of events in any evolving accident must be quickly predicted.

Radioactive iodine ^{131}I is the most dangerous and relatively the most abundant isotope released during any serious accident of a nuclear reactor. Normally small amounts of stable iodine from the environment are absorbed by the thyroid gland. Released in accident ^{131}I inhaled with air or taken in with contaminated food is also absorbed by the gland. Such accumulated radioactivity may cause thyroid cancer. Therefore, any discussion of health consequences of nuclear accidents in humans must start with estimation of thyroid exposition to ^{131}I versus distance to the reactor and versus time after the accident moment. Drop of exposition with time is governed by half-time: after some specific time (characteristic for any given radioisotope) its activity drops by half. ^{131}I half-time amounts to about 8 days.

Unfortunately, nuclear power plant accidents release also radioisotopes of much longer half-times that may contaminate soil and ground waters for significantly longer periods. The most abundant among them is caesium-137 (^{137}Cs) with approximately 30 years half-time. Radioactivity measured after an accident in the environment for the most part is just from ^{137}Cs. Exposition to radioactive contaminants in the environment drops with time not only because they decay, but also because they may soak into deeper layers of soil, be flushed out of soil into deep rocks, or carried away by rivers to seas where their influence on humans is negligible or none.

As we have already mentioned, two concentric zones must be defined around each nuclear power plant: smaller Restricted Usage Zone and larger Emergency Planning Zone. Manufacturers of some state-of-the-art reactors are bragging that their reactors may be surrounded by zones of radiuses as small as less than 0.8 km (the former zone) and 3 km (the latter zone). Polish law requires that:

- no action is necessary outside the Restricted Usage Zone (which in case of state-of-the-art reactors practically ends at the power plant fence) for events expected more frequently than once in 10 000 years
- no prompt (sudden) action is required within the Emergency Planning Zone for events expected less frequently than once in 10 000 lat years but more frequently than once in 1 000 000 (one million) years; other interventions within that zone are accepted
- interventions outside the larger zone are accepted only in case of an event expected less frequently than once in 1 000 000 (one million) years.

Generally, the regulations implement a globally accepted rule that more dangerous events must be less probable.

6.1 Serious accidents

Reactor core meltdown is qualified as a serious accident. Probability of such events is tiny (see the next section), but by no means equal to zero. After the Three Mile Island plant accident possibility of a serious accident became an essential part of every analysis of safety of any nuclear reactor. However, till these days the occurred events have not been fully modelled and their sequences of mishaps fully understood. Experimental recreation of core melt down would be very expensive, therefore main efforts are put on development of software codes that can model the occurring processes and thus help to analyse such events in older and newly-designed reactors.

Radiographic images of fuel rods destroyed in result of a partial meltdown of the tested fuel cassette (obtained within framework of the PHEBUS project) are shown in Fig.24. FPT0-FPT2 images show fuel rods and control rods used in typical PWR reactors. Release of fission products to safety containments filled up with various amounts of steam was also investigated.

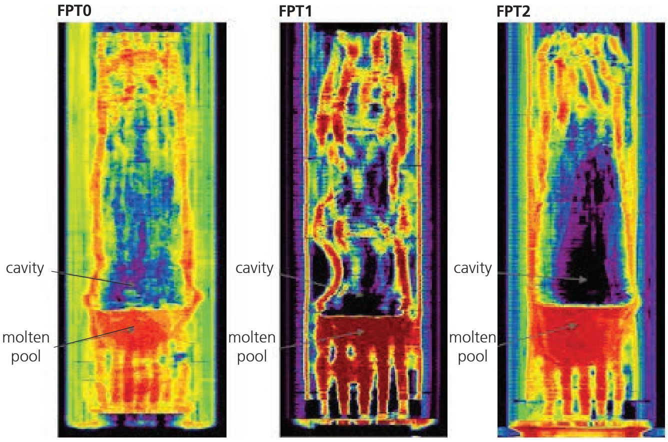

Fig. 24 Radiographic images of fuel rods destroyed in result of a partial meltdown of the tested fuel cassette (obtained within the PHEBUS project) (source: http://www.irsn.fr).

Another test (FOREVER) was performed to see how reactor pressure vessel behaves under the influence of a molten reactor core. Images of the vessel bottom are shown in Fig.25. Brighter regions in the image represent higher temperatures of the corresponding vessel fragments. Bottom images show situation after the vessel wall has been burnt through (an outflow seen to the left of each image). The last image shows the damaged vessel after the test. The acquired experimental data helped to develop and/or verify software codes capable to model serious accidents.

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[13]mSv (millisivert) is an unit of measure of ionising radiation equivalent dose, i.e. dose with health effects taken into account. Health effects may be different for different kinds of radiation even at identical absorbed dose (mGy). To get mSv multiply mGy by quality factor (QF) characteristic for the given radiation type.

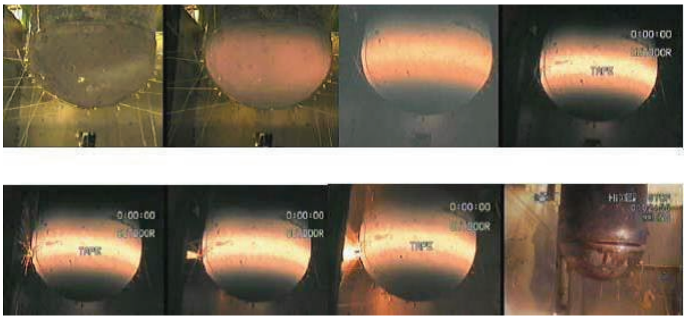

Fig. 25 Behaviour of reactor pressure vessel under the influence of a molten reactor core (obtained within the FOREVER project) (source: Ex-Vessel Coolability and Energetics of Steam Explosions in Nordic Light Water Reactor, H.S. Park and T.N. Dinh, Royal Institute of Technology, Sweden).

As we have already mentioned, one of the challenges that designers of the 3rd generation reactors must face is that power plant construction must prevent release of radioactive substances outside reactor safety containment even in the very improbable (although possible) event that the reactor core is molten down. To that end safety systems must effectively cool the molten core down.

In modern constructions, the issue of a serious accident is approached in two ways. First, designers strive not to let the molten core outside the reactor vessel. Steel vessel wall is cooled down by outside water, see Fig.26. Such approach have been implemented in the Westinghouse AP 1000 reactor. In the other approach, a possibility that the molten core will burn through the reactor steel vessel wall is accepted; it is envisioned that the molten debris will flow down to a special tank under the reactor vessel, called core catcher (see Fig.27). Core catcher is made of some refractory materials of a very high melting point.

Let us talk a bit about the probability of melting a reactor core down.

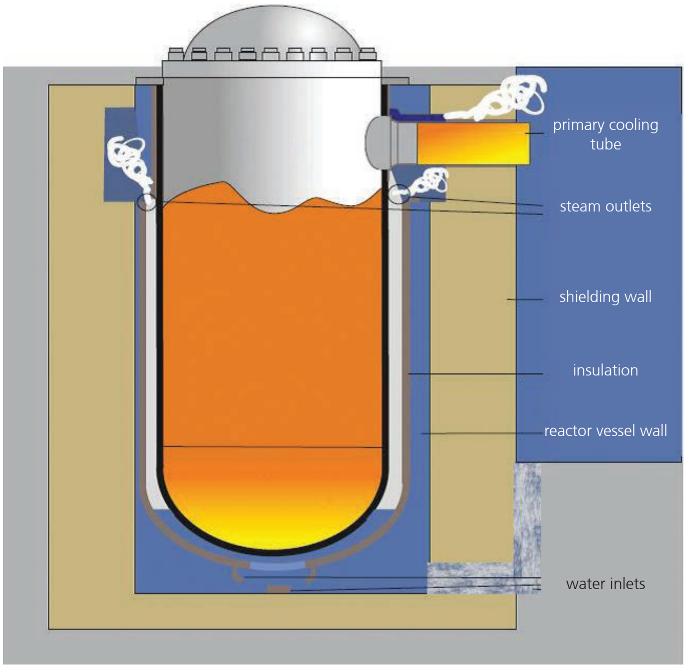

Fig. 26 Westinghouse AP 1000 reactor vessel is cooled down by outside water that carries away heat transported through vessel walls from molten core, protecting the walls against being burnt through.

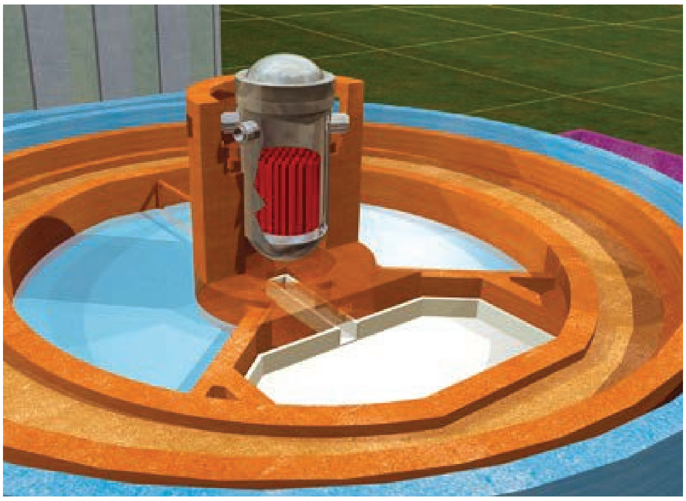

Fig. 27 Areva EPR reactor core is situated above the so-called core catcher (depicted white). Should the reactor core melt down and the reactor vessel wall be burnt through, the molten core will flow down into the catcher.

6.2 Core meltdown probability

Core *meltdown* may happen when all reactor safety systems have failed. They may fail since reliability of each and every technical device (for example a valve) is finite. Probability that a valve fails is measured simply by expected (average) number of valve open/close operations before it will not respond to the issued command[13]. Majority of reactor safety system building blocks are commonly used in various process industries, hence their individual reliabilities are well known. Safety systems are composed of groups of various elements grouped in different ways. Special analysis techniques collectively called *probabilistic safety analysis* are used to determine failure probability for the entire group/system.

Core meltdown event itself does not pose a substantial threat to population until reactor safety containment – the last barrier – keeps the probability of releasing radioactive substances into the environment at a very low level. Nevertheless, designers strive to keep core meltdown probability as low as reasonably possible, see table below.

Reactor type	**Core meltdown probability (per year)**
ESBWR	$2.0\cdot10^{-8}$ = 0.0000000**2**
ABWR	$1.0\cdot10^{-7}$ = 0.000000**10**
AP 1000	$5.1\cdot10^{-7}$ = 0.000000**51**
Currently operated plants	$5.0\cdot10^{-5}$ = 0.0000**5000**

The above data are results of probabilistic safety analyses conducted by respective manufacturers. What does the $1.0\cdot10^{-7}$/y probability of ABWR reactor core meltdown mean? Well, it means that serious accidents in nuclear power plants with ABWR reactors are expected once in 10 million years of reactor operation. A serious accident among all 435 reactors currently operated in the world (according to IAEA data) is expected once in $435/(5\cdot10^{-5}) \approx 10$ years. If all those reactors were replaced with 500 times more reliable ABWR constructions, frequency of serious accidents would drop to about once in 5 000 years.

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[13] For example, if a valve gets stuck after 1,000 successful operations, its failure probability is 1/1,000 = 0.001.

6.3 Conclusions

Reactor failures are very rare events, but they cannot be completely excluded just like failures of other technical devices. Sixty-year-long history of commercial nuclear power industry has witnessed just a few serious accidents, of which only one killed 28 people by acute radiation sickness (Chernobyl). That fact is an experimental confirmation of extraordinarily high safety standards already implemented in nuclear power plants. However, even if number of direct victims may be relatively low, the Fukushima accident has shown that social consequences of nuclear accidents may be very extensive. Therefore societies fear nuclear power. Also therefore safety systems are constantly improved beyond levels implemented in any other process industry, which unfortunately is associated with soaring developmental costs. Nuclear power must cope with that serious challenge.

7. NUCLEAR ACCIDENTS: CAUSES, CONSEQUENCES, DRAWN LESSONS

Each serious accident should be (and indeed has been) very carefully analysed to draw every applicable lesson for the future. Information, conclusions, and recommendations are supplied to operators of all nuclear power plants to prevent failure in their plants as much as possible disregarding any possible commercial or confidentiality considerations. Safety is here an absolute priority before commerce.

Let us repeat that sixty-year-long history of commercial nuclear power industry has witnessed just a few serious accidents, of which only one killed 28 people by acute radiation sickness (Chernobyl). That number of victims is insignificant compared to the number of victims of other industrial disasters that took place during those sixty years.

Unfortunately, another very important aspect makes that picture (quite bright for nuclear power industry, isn't it?) much more gloomy. In the A-/H-bomb times just after WW2, very low levels of exposition to ionising radiation were officially recognized as health hazard. Since those low thresholds were exceeded within relatively large-radius zones around damaged plants in both Chernobyl and Fukushima, both involved authorities made their decisions to resettle all residents of those zones. Huge stress felt by people resettled from their homes, rooted out of their jobs, deprived social security feeling, as well as panic fear against ionising radiation have taken a very heavy toll. Social consequences of the Chernobyl accident include more than 100 000 unnecessary abortions, increased drunkenness, more suicides. Approximately 1 million people are still affected by various psychic or somatic diseases by no means related to radiation; they also are indirect accident victims even if not radiation victims. Social consequences of the Fukushima accident include more than 1 000 stress-deceased persons among the displaced people. Various estimates show that only a tiny fraction of the resettled persons really needed to be resettled. Life expectancy of overwhelming majority of the displaced persons would be possibly shortened by just 1 week (statistically) should they remain in their homes and absorb radiation dose resulting from the somewhat increased exposition level several kilometres away the damaged plant.

7.1 INES nuclear event scale

International Atomic Energy Agency has identified 7 severity of radiation-involving events in the form of the so-called International Nuclear Event Scale (INES). The scale has been used since 1990[14] in 60 countries (including Poland) to rate accidents in nuclear facilities (excluding events in nuclear medicine).

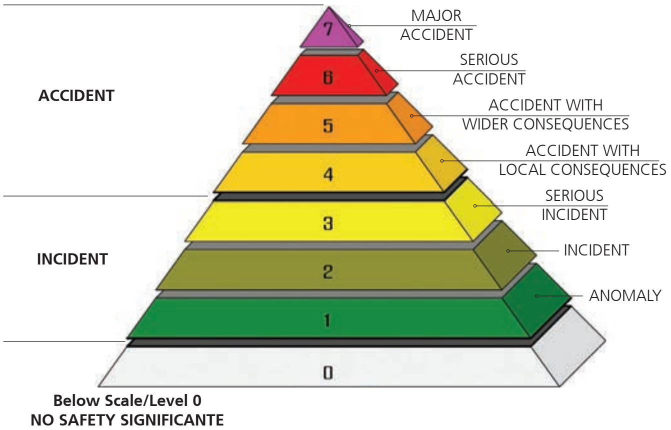

Fig. 28 International Nuclear Event Scale (INES).

Level 0 events are departures from established procedures that do not impact plant safety. Such departures are pretty frequent, for example more than 100 level 0 events are noted each year in French nuclear power plants[15].

Level 1, 2 and 3 events are collectively referred to as *incidents*. Level 2 event ("incident") means a significant radioactive contamination and/or excessive exposition of plant personnel to ionising radiation. Level 3 event ("serious incident") means exposition of general population to permissible doses of ionising radiation, or a serious radioactive contamination, or acute health consequences in some facility employees occupationally exposed to ionising radiation.

Level 4-7 events on the INES scale are collectively referred to as *accidents*. Level 4 events are accidents of only local consequences. In effect, general population may be exposed to permissible doses of ionising radiation, reactor core may be significantly damaged, some facility employees occupationally exposed to ionising radiation may be irradiated with fatal doses. Event that occurred in Tokai-Mura (Japan) nuclear fuel processing facility in 1999 was a level 4 accident: a solution containing uranium unintentionally reached criticality, and the emitted strong radiation killed 3 employees.

Level 5 accidents may have wider than local consequences. In such cases some of the planned emergency actions must be implemented to avoid a disaster and/or to prevent health consequences to general public/environment pollution. Reactor failure in the Three Mile Island plant that occurred in 1979 was an example of level 5 accidents.

Level 6 events are serious accidents i.e. *accidents*, in which significant amounts of radioactive materials are released. The situation might call for implementation of the entire emergency actions plan. Event that occurred in Kyshtym (former Soviet Union) nuclear fuel processing facility in 1957 is the only accident in history rated 6 at the INES scale.

Level 7 events are major accidents, in which very high amounts of radioactive materials are released, therefore health consequences to general public/environment pollution are extensive. Wide-ranging emergency actions must be applied. Chernobyl (1986) and Fukushima (2011) are the only accidents in history rated 7 at the INES scale.

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[14] The latest revision is dated 2008.

[15] After the "Everything about nuclear power. From atom A to zirconium Zr" Areva brochure (ed. 2008)

Release of large amounts of radioactive fission products (mostly ^{131}I and ^{137}Cs) is among the most serious consequences of severe/major nuclear accidents. The former is dangerous since it accumulates in thyroid and may give rise to thyroid cancer. 30 years halftime of the latter is also a big problem if it has significantly polluted soil/ground waters within large areas around the damaged plant: the pollutant increases local radiation levels and may contaminate human bodies with food/water. People fear also plutonium considered a strongly toxic element even if the so far collected experience has not confirmed its extraordinary toxicity. In any case, the Chernobyl accident was the only accident in history of commercial nuclear power industry, in which plutonium was released during the several-day-long fire of nuclear fuel. In other cases plutonium oxide turned out to be relatively immobile due to its weak solubility in water.

Five of the most serious accidents in history of commercial nuclear power industry: Browns Ferry (USA) 1975, Three Mile Island (USA) 1979, Chernobyl (former Soviet Union) 1986, Paks (Hungary) 2004, Fukusima (Japan) 2011, are discussed below. Accidents in the Chalk River, Oak Ridge, Idaho Falls research reactors (USA) were less severe: nobody lost life, reactor damages were limited. However, in the Vinca (former Yugoslavia) accident in 1958 one person lost life, and four other lives were endangered.

Fig. 29 The Browns Ferry nuclear power plant.

7.2 Browns Ferry (1975)

Neither construction nor operation of BWR reactors installed in the Browns Ferry nuclear power plant played any significant role in the 1975 accident. It was fire induced by two electricians trying to seal air leaks in cable tray penetrations. To that end they were using strips of spongy foam rubber. They were also using candles to determine whether or not the leaks had been successfully plugged by observing how the flame was affected by air flowing into the reactor buildings (negative pressure is maintained in reactor buildings to prevent release of radioactive substances into the environment in case of any accident). Unfortunately the air flew so fast that the candle flame was bent towards the foam and ignited it.

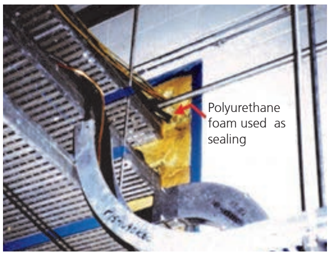

Fig. 30 Typical cable tray penetration (source: Wikipedia Commons).

The ignited fire was so difficult to put out that about 2 000 various cables burnt out on an area of about 9 x 12 metres. No radioactive substances were eventually released into the atmosphere, but it was a challenge to maintain proper cooling of the reactor during and after the fire. Therefore the entire event was treated very seriously. The recommendations included to eliminate flammable materials, to separate power cable routes from signal cable routes and to separate cables routed to redundant sub-systems. Besides, a number of conclusions regarding organisation of plant operation were drawn.

The Browns Ferry event was not the only fire in a nuclear power plant. Probably the most profound consequences were drawn after the fire in the Armenian power plant (former Soviet Union) in 1983. Modifications of the fire protection system (including reconstruction of rooms) took several months to implement, during which period the plant was shut-down. The fire revealed also some threats that plant managers were not aware of. Direct damages were estimated for about $10M, but 6-month long not planned shutdown brought about losses on the order of $ 400M (lost profits, cost of purchase of missing energy from other power plants etc.[16]).

7.3 Three Mile Island (1979)

Accident in the Three Mile Island power plant in Pennsylvania (USA) is often quoted as a severe accident rated 5 at the INES scale. Even if a PWR[17] reactor core melted down, the event had no serious consequences either for personnel or for the nearby residents. The failed reactor is visible to the right of the photo shown in Fig.31.

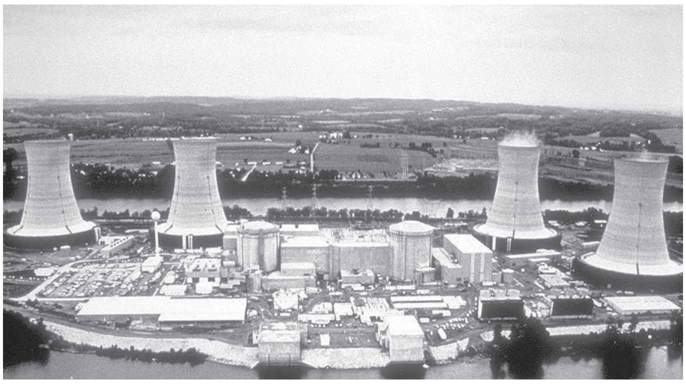

Fig. 31 The Three Mile Island nuclear power plant before 1979 (source: Wikipedia Commons).

Briefly, chain of events was as follows. The TMI-2 reactor was operated at practically full power. Because of a failure within the compressed air system, valves regulating circulation of water through the reactor secondary cooling loop were shut down. Temperature in the primary loop was increasing and in a few minutes entire available secondary water was vaporized inside steam generator. The reactor was still increasing primary loop water pressure. As soon as safety threshold was exceeded, automatic control systems shut the reactor down within about 1 second. Safety valve over the pressure stabilizer opened up (as it should) to release overpressurised steam to the dump tank, but unfortunately did not close after the prescribed 10 seconds, which fact was missed by the operators. In result cooling water started to leak outside the primary loop and soon the reactor lost its cooling. Inadequate automation (no signal that the safety

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[16] http://www.nrc.gov/reading-rm/doc-collections/nuregs/brochures/br0361/s1/sfpe1.pdf

[17] PWR reactor construction was described in the first brochure L.Dobrzyński, K. Żuchowicz, "Energetyka jądrowa: Spotkanie pierwsze", NCBJ (2012); http://ncbj.edu.pl/materialy-edukacyjne/materialy-dla-uczniow (PDF, 7.1 MB, in Polish)

valve stuck, missing core water level gauge) coincided with inadequate operator training (they misinterpreted signal of high water level in pressure stabilizer as a high water level in the core, did not realize that the reactor was losing its cooling, and disabled the UACR emergency cooling system).

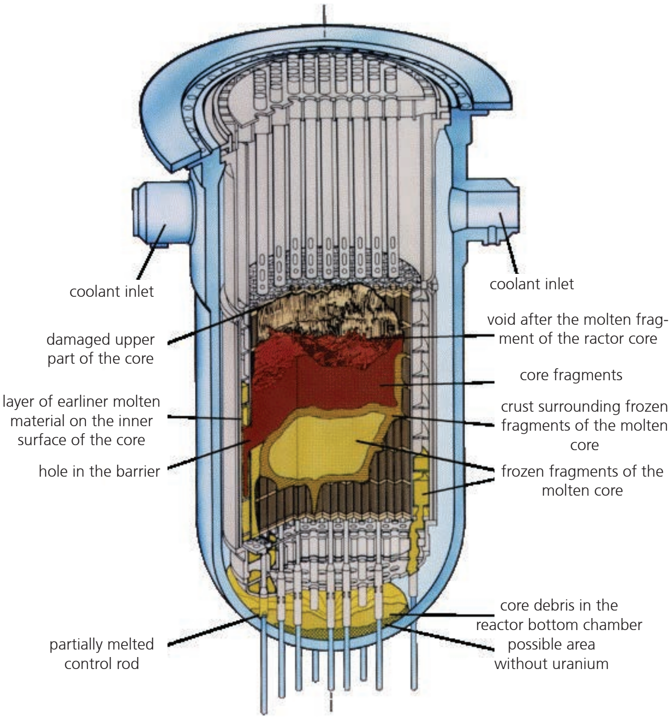

Fig. 32 TMI-2 reactor core after the accident (source: Wikipedia Commons).

Let us repeat that even such severe accident which caused substantial damages had no serious consequences either for personnel or for the nearby residents. Safety containment was intact, very little radioactive substances were released to the atmosphere, no terrains around the plant were contaminated. The molten core was properly cooled down, reactor behaviour was stable. Pennsylvania governor ordered temporary evacuation of approximately 3 500 pregnant women living within the 5 miles (about 8 km) radius around the damaged plant in view of small releases of radioactive substances. No harmful effect to any resident or plant staff was ever evidenced.

To remove about 100 tonnes of nuclear fuel from the destroyed reactor was a serious challenge. That long and complicated process finally ended in early ’90. The TMI-2 reactor was finally disassembled in 1991 during 12 days at a cost of $ 973M.

The lessons drawn from the accident and deployed in ‘80 included: (i) automation circuitry installed in PWR reactors of that type operated all over the world were improved; (ii) extensive emergency procedures based on failure symptoms available in plant control rooms were elaborated (the procedures eliminated more than 90% of all possible operator errors); (iii) a new training system for reactor operators was devised; (iv) a dedicated government agency whose task was to analyse and evaluate nuclear power plant operational data to better asses reactor safety was called into being.

7.4 Chernobyl (1986)

Four reactors operated (and two other under construction) in the Chernobyl (former Soviet Union, currently Ukraine) nuclear power plant were neither PWR nor BWR designs. After their name in Russian (meaning Large Power Channel Reactors) they are known as RBMK. RBMK peculiar reactors are water-cooled, but additionally graphite is used as neutron moderator. Channel design enables refuelling during operation. Besides, a large number of individual channels precludes a chance that cooling of the core is completely lost (at least according to reactor designers). The reactor may be used to produce ^{239}Pu, a fissile plutonium isotope with military applications.

As can be seen in Fig.33, dimensions of RBMK reactors (diameter 12 m, height 7 m) are significantly larger than dimensions of typical PWR or BWR constructions (3.3 m, 3.6-3.8 m, respectively). Therefore power levels generated in RBMK reactors are much more difficult to control.

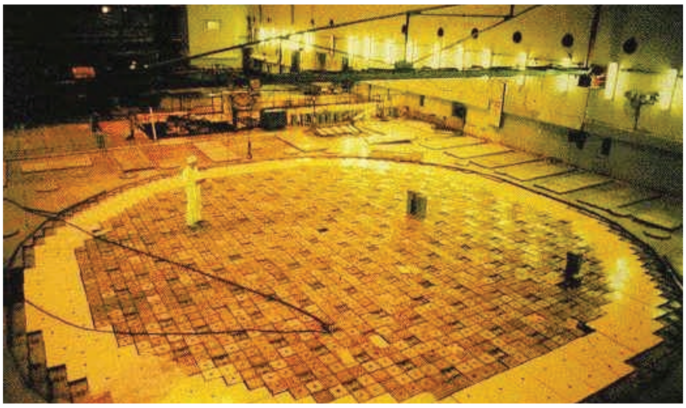

Fig. 33 RBMK reactor top view. Visible 25 x 25 cm squares hide 2,488 blocks of graphite moderator, 1,661 pressurized channels with fuel rods cooled down by flowing water, and 222 blocks with control rods.

In spite of multi-year experience of Soviet designers, RBMK was a dangerous construction since it could become unstable in some circumstances. Graphite heated to about 700°C (temperature of the graphite moderator in RBMK reactors) must be prevented against getting in touch with air or else it ignites. To that end RBMK reactor core was placed inside a tight steel vessel. However, the reactor had no safety containment. Relatively long time (about 20 s) was necessary to shut the reactor down in emergencies. Just after control rods started their travel towards the core, reactor power was first rising to drop eventually in a later shut-down phase.

On the night the disaster hit operators were conducting an ill-planned experiment requiring that reactor safety systems were temporarily disabled. Some operator errors caused sudden increase of reactor power/steam pressure. Water vaporized, steam reacted with zirconium contained in fuel element cladding, hydrogen was produced. The core melted down. Chemical explosion of steam and hydrogen resulted. Reactor vessel and building was demolished. Huge amounts of radioactive gases, aerosols, graphite fragments and core debris were released to the atmosphere. Fire caused by self-ignited graphite spread quickly all over the place.

5 000 tonnes of concrete, sand and other materials were dropped down from choppers to put out the fire and to stop release of radioactive dust into the atmosphere. Since exposition to radiation was very high, acute radiation syndrome developed in 134 rescuers working around the fire and flying above it, of which 28 died soon. Three more

fatalities were immediately caused by mechanical injuries and heart attack. 19 out of the remaining 106 cured rescuers died before 2010, which is normal fatality rate for such a group in 24 years. Large doses of radiation were absorbed also by about 1 000 other persons. Approximately 600 000 persons were working in the years 1986 and 1987 to clean up the destroyed plant and 30-km-radius contaminated zone around it. About 6 700 thyroid cancer cases have been noted till now, fortunately majority of them should be fully treatable. Children comprise a significant fraction of the victims (perheps ~15 death).

The destroyed reactor itself is currently (2015) covered with a massive concrete structure called "sarcophagus" (Russian and Ukrainians call it "shelter object"). It is to be soon replaced with another shield (see Fig. 34) that would enable to proceed with demolishing works on reactor remnants. By the way, Mostostal, a Polish company, won a 7.6 million Euro worth contract to deliver 105 m high, 150 m long, 257 m wide steel dome for the shield.

Fig. 34 Sarcophagus constructed by the NOVARKA French company (state as of April 26, 2014; source: http://footings.wordpress.com/2011/04/20/cannibal/.

Economic costs of the Chernobyl accident may be assessed to $13-14 billion.

Technical investigation of the event has revealed the following weak points in the RBMK construction:

- positive reactivity if cooling water starts to vaporize (bubbles) – while all conventional reactors exhibit negative reactivity in such conditions i.e. each safe reactor tends to shut itself down if something goes wrong
- relatively slow operation of emergency shut-down circuitry, and transient power surge initially after control rods started their travel towards the core
- easiness with which reactor safety systems could have been disabled
- no safety containment.

It was also revealed that basically similar failures of other RBMK reactors occurred already in 1975 (the Leningrad-1 nuclear power plant) and in 1982 (Chernobyl-1). Consequences of both events were much less severe. Unfortunately, the Soviet system of circulating sensitive information did not allow to draw all lessons from those events.

Wind directions changed frequently (see Fig. 35), so released radioactive materials trans-ported by air were contaminating significant areas, both around the plant and far away. The highest ^{137}Cs fall-out was found in the plant vicinity (1.48 MBq/m^2). 336 000 people from terrains considered dangerously polluted (fall-out more than 37 kBq/m^2) of total area of about 146 000 km^2 was forcibly resettled. However, nobody was resettled from similarly polluted territories in Poland, Norway, Sweden, Finland, UK, Austria, Switzerland or other European countries. Natural background radiation level around Chernobyl before the accident was about 2.5 mSv/y. On April 26, 1986 exposition soared to 8 760 mSv/y, but dropped down to about 19 mSv/y just one week later, and to about 3.5 mSv/y one month later. Currently (2014) in various points located about 4 km away the damaged reactor exposition to ionising radiation roughly corresponds to global average i.e. is smaller than exposition of the general public strolling the Plac Defilad square in the Warsaw downtown (which square is paved with granite flagstones).

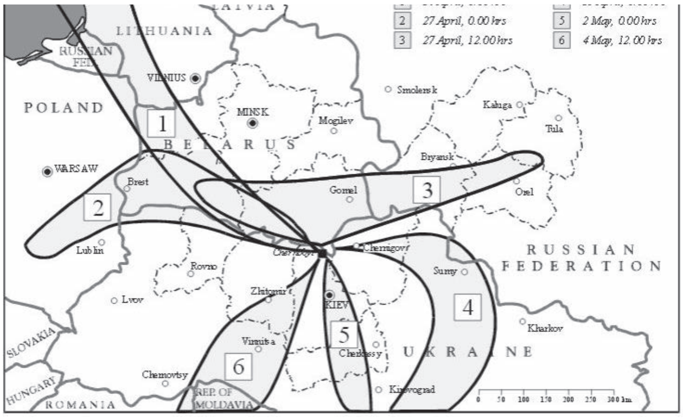

Fig. 35 Radioactive substances from Chernobyl were transported by winds of frequently changing directions. Therefore radioactive fall-out covered diverse areas at different distances to the damaged power plant.
Source: UNSCEAR http://www.unscear.org/docs/reports/2000/Volume%20II_Effects/AnnexJ_pages%20451-566.pdf.

Even if the Chernobyl accident ranks among the two most severe accidents in the history of civil nuclear power industry (rated 7 at the INES scale), it directly killed only some rescuers but no one from the general public. Incidence rate of leukaemia or other cancer types – except for the easily curable thyroid cancers – has not increased till these days. Cancer deaths generally account to 20% of human mortality rate. Therefore 4 000 additional radiation-traceable cancer deaths predicted in the future by Chernobyl Forum (a group of 8 UN agencies plus governments of Belarus, Russia and Ukraine founded in 2003 to scientifically assess health effects and environmental consequences of the Chernobyl accident and to issue factual, authoritative reports on its environmental and health effects) will be statistically unnoticeable. UNSCEAR[18] data show that cancer incidence rate among inhabitants of Russian territories polluted by Chernobyl fall-out is by 5-7% lower than the average rate observed in the entire population of Russia. The rate among survived rescuers is also lower by 15-30%. On the other hand population of displaced persons is really plagued by various psycho-somatic diseases.

To-day the largest UN agencies (WHO, UNICEF, UNSCEAR) do not see any reasons not to let people return to the territories once considered "polluted" and evacuated.

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[18] United Nation Scientific Committee on the Effects of Atomic Radiation was established in 1955 to "define precisely the present exposure of the population of the world to ionizing radiation".

7.5 Paks (2004)

Four WWER reactors (Russian equivalent of PWR) each of 500 MWe power are operated in Paks nuclear power plant (Hungary, see Fig.36). Nuclear incident rated 3 at the INES scale occurred on April 10, 2003 when some used fuel rods were cleaned in a dedicated tank outside the reactor (see Fig.37). The cleaning is necessary to remove oxides that build-up with time of operation on surfaces of the rods and impair their thermal contact with the coolant. To perform the cleaning, the rods are immersed in suitable solutions. That time the rods were left over for some time in empty tank before being flooded with water. However, significant amount of heat generated in fuel rods removed from every reactor core (decay heat) has risen in the meantime temperature of the left-over rods so high, that the poured water immediately boiled and vaporized. In result cladding of 30 fuel elements broke and steam exploded completely destroying the elements.

Fig. 36 The Paks nuclear power plant.

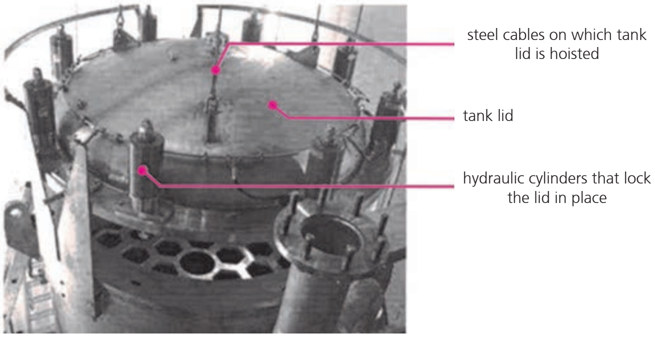

Fig. 37 Dedicated tank used in the Paks nuclear power plant to clean used fuel rods.

It was Hungarian National Atomic Energy Agency who was to blame in the first place. They have failed to verify the fuel rod cleaning technology proposed by Siemens (vendor) who of course claimed that the technology was well-proven and reliable). A new technology had to be implemented. After a year-long break the reactor resumed operations and has been normally operated till these days. Nobody was injured in the course of that incident.

7.6 Fukushima (2011)

The last of the accidents we are going to discuss here occurred on March 11, 2011 in the Fukushima Daii-chi nuclear power plant (Fig.38). First, a strong earthquake (9.0 in Richter scale, soil acceleration on the order of 5 m/s^2) hit. In '70 when the plant was designed such strong earthquakes were thought of as improbable. In spite of being old 2nd generation BWR designs, intact safety circuitry automatically shut all six reactors of the plant down. However, the earthquake destroyed all lines that supplied machinery within the plant with power, hence Diesel emergency generators had to take over power supply.

Unfortunately, the earthquake was soon followed by a tremendous tsunami wave. The wave was several metres higher than the worst predictions. Original plant building permit required to prepare all plant building structures for tsunami waves of height up to 3.1 m. Embankments were later heightened up so at the moment the tsunami hit they could protect the plant against waves of height up to 5.7 m. However, the wave that actually hit was about 15 m high. Such waves were the last time seen in that location probably back in 9th century.

Fig. 38 Fukushima Daii-chi nuclear power plant (photo TEPCO, plant operator).

Tsunami water flooded and in consequence made inoperational 10 out of 13 Diesel generators and all electrical circuits; besides, some Diesel fuel tanks were flushed away to the ocean. Two Diesel generator situated at somewhat higher elevation remained operational, but they could not effectively supply power to their loads since the switchgear was flooded. The only useful Diesel generator continued to supply power to reactors 5 and 6, and they survived intact the tsunami.

The remaining reactors were completely devoid of cooling. Potential consequences of that fact were dreadful. Rescuers first tried to pump water into the reactors safety containments using some portable pumps and salty water from the ocean (as soon as available reservoirs of fresh water were exhausted). However, because of a high overpressure inside the containments it was a very inefficient operation. Then they tried to relieve surplus of steam from the containments into the atmosphere at the price that some radioactive materials were also released. Their efforts were in vain: one day after the earthquake, the overheated steam and hydrogen mixed with atmospheric oxygen and exploded in reactor 1 building. Two days later similar explosion occurred in reactor 3, several hours later – also in reactor 2. Reactor buildings (Fig.39) together with some of the spent fuel storage water pools located in their top parts were practically demolished.

Course of actions in other nuclear power plants operated that time in Japan ended with much less disastrous results. Another nuclear power plant operated in Fukushima close to the Daii-chi plant – Daini or Fukushima 2 – was also flooded by the tsunami wave, but Diesel generators were not made inoperational and reactors were not damaged.

Fig. 38 Fukushima Daii-chi nuclear power plant (photo TEPCO, plant operator) Fig.39 Demolished reactor buildings in the Daii-chi nuclear power plant (source: Wikipedia Commons).

That was possible because the wave was "only" about 9 m high at that place. However, it was enough to flood pump stations in the plant. For several days hot water could not be efficiently pumped to the ocean. During that time some steam from reactor safety containments had to be released (together with some radioactive substances) directly into the atmosphere. No serious consequences have been noted, and the event was finally classified as INES-3. Onagawa nuclear power plant operated about 100 km away Fukushima survived similar earthquake and tsunami without any damage. Its operator took much better care of its safety locating it higher than the Daii-chi plant. 4.5 metres high tsunami wave flooded also one of the pump stations in yet another Tokai Daini nuclear power plant, but no serious consequences ensued.

Consequences of the Daii-chi plant accident are serious and much time will be needed to clean the site up. The Japanese government decided to entirely dismantle the heavily damaged plant. To that end many obstacles have already been overcome, but even more have yet to be overcome. First, the site had to be cleared of all debris ferried by the flood. It was a tricky operation since the debris was mixed up with radioactive fall-out of various substances released during explosions. This task has already been accomplished with the help of some remotely controlled equipment (excavators, dump trucks etc.). Radioactive dust deposited on building walls was immobilized with the help of a special adhesive sprayed on the walls. Temporary weather shelters have been built around the damaged buildings to facilitate dismantling works. The next task is to pull stored fuel rods off the reactor pools. This operation has been already completed in reactor 4 (where access to the pool is easiest), in other reactors it is under way. Damaged reactors and their molten fuel cannon be taken care of until all the rods are removed.

Simultaneously, the plant operator must all the time cope with the problem of contaminated water. Since decay heat must still be carried away from the molten reactor cores, water has been pumped into the damaged reactors all the time since the accident – although the heat generation rate is slowly dropping down and volumes pumped now are by far smaller than those necessary just after the accident. The pumped water is constantly leaking via various leaks to building basements where it is mixing up with ground waters inflowing via cracks in foundations. It has been impossible to locate and stop the leaks/ cracks because of a still dangerous radiation level and the degree of demolition. Therefore plant operator is constantly pumping out the contaminated water from the basements into some temporary storage tanks (about 400 m^3 a day). The tanks have taken up majority of plant premises, their total volume is about 400 thousand m^3. A facility to filter/decontaminate the water has been put into operation, nevertheless even the treated water is still somewhat radioactive and the operator has not been granted an official permit to dump it into the ocean. To solve the water problem a barrier that would stop inflow of ground waters to basements was started. The barrier will consists of a strip of frozen soil around the plant. The soil freezing technology is commonly applied to protect excavations at construction sites, however it was never implemented on such a large scale. Another ad hoc solution was temporarily implemented: all wells located above the plant are constantly pumped out and the collected water is dumped directly to the ocean. That way ground waters have no chance to mix with the contaminated water from the damaged reactor buildings.

The Fukushima accident is comparable to the Chernobyl accident. Failure of reactors 1-3 has been finally rated an INES accident 5, while the entire Fukushima accident – an INES 7 accident[19]. Map of soil contamination by ^{134}Cs+^{137}Cs fall-out around Fukushima is shown in Fig.40. However, it must be pointed out that the latter accident caused neither any deaths nor any ionising radiation-related sicknesses (except – perhaps – a small number of thyroid cancer cases). Exposition in the most heavily contaminated areas amounted to 798 mSv/y, while the official *tolerable dose limit* in force before 1955 was set to about 680 mSv/y (in 1955 the official radiation protection limits were made more tough). Of course other severe problems (molten reactor cores, demolished buildings, radioactive dusts, contaminated water) remain to be solved, and are successively being solved.

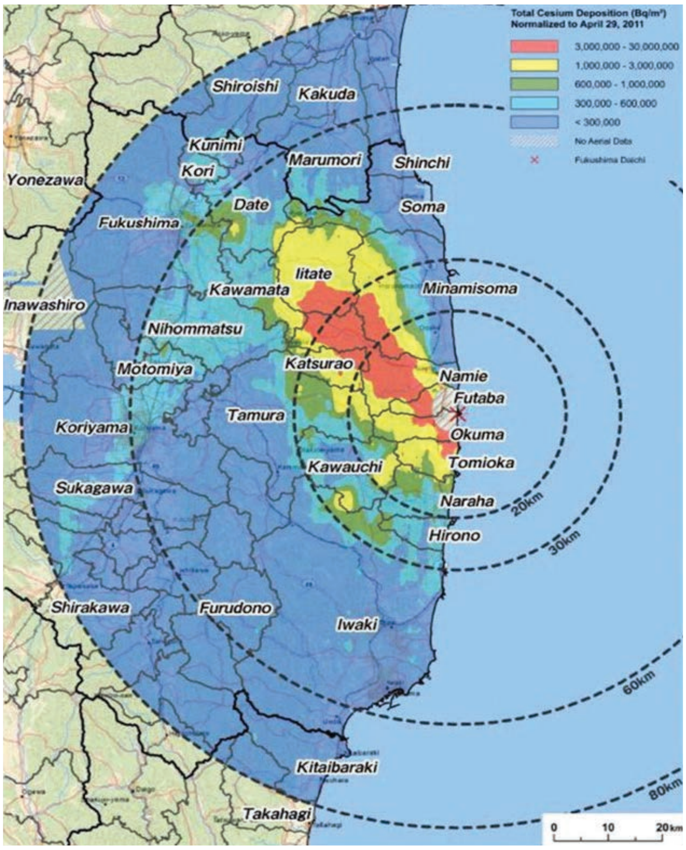

Fig. 40 Radioactive fall-out (^{134}Cs + ^{137}Cs) around the Daii-chi nuclear power plant in Fukushima. Soil contamination above 3 MBq/m2 is depicted red. (http://www.iaea.org/newscenter/news/2011/fukushimafull.html after MEXT Japan agency data, June 2, 2011).

[19] http://www.bbc.co.uk/news/world-asia-pacific-13045341

Just like in Chernobyl, authorities commanded resettlement of 70 000 inhabitants, 90 000 others resettled voluntarily. Various psycho-somatic diseases are observed in population of the displaced persons. More than 1 500 persons died prematurely because of a high stress. No extra exposition to radiation traceable to consumption of potentially contaminated food/water was noted.

It is quite interesting to compare tremendous public interest in consequences of tsunami-related nuclear accidents (which reflects anti-nuclear radiophobia prevailing in the societies) with almost complete lack of interest in horrendous consequences of the natural disasters. Earthquake & tsunami flooded with salty waters about 500 km^2 of land, including 200 km^2 of arable land. The losses included:

- 18 493 death toll, 2 683 missing persons, 6 217 persons injured[20]
- more than 250 000 totally demolished buildings, 500 000 others – partially damaged
- 22 000 fishermen boats destroyed
- flooded arable land will have to be excluded from agricultural production for a few years.

These are the real problems for Japan. Consequences of a reactor failure may be extremely costly, but each such failure is just another industrial accident manageable by respective professional services. Post-Chernobyl experience have shown that there are no grounds to expect any significant number of extra cancer cases in the future. Anti-nuclear propaganda unleashed after the Fukushima accident reinforces impression of a threat that de facto does not exist as shown by numerous reactor *stress-tests* conducted in many countries. The tests have confirmed a high degree of safety of nuclear facilities.

7.7 Main goal: to eliminate human errors

Conclusions drawn from the past failures of nuclear power plants have shown that many of them could have been avoided if only the personnel running the given plant behaved correctly. Therefore one should seek various means to minimize the risk of mistakes made by staff of nuclear power plants. Several lines of approach are briefly discussed below.

- Number of gauges installed in nuclear power plant control rooms is as low as practically possible: only the most essential ones. Their location is carefully optimized.
- Each plant operator is trained for a period of at least 3 years. Already licensed operators are regularly trained on plant simulators (made to the 1:1 scale), where various possible scenarios may be realistically recreated.
- No plant may be operated by less than three persons: two licensed operators plus an expert on safety systems.
- Safety systems must be designed in such a way that no mistake of a single operator may in consequence damage the reactor core. At least one safety/control system must react to the mistake (e.g. to raise an alert, to turn some auxiliary system on etc.).

In any emergency operators act under heavy stress. Therefore contemporary safety systems should guarantee that no serious accident may happen in a time shorter than about 30 minutes. Plant operators may use that time to properly and effectively react to any noticed irregularity. Actually, during that time they are supposed to just supervise safety/control systems checking whether all subsystems are turned on in due time and sequence.

8. TRENDS IN CONSTRUCTION OF NUCLEAR REACTORS

New power rectors have not been recently commissioned. However, their designs have been systematically advanced to increase their safety on one hand, and to get ready for inevitable rise in global demand for electric energy on the other. A few such ideas will be briefly presented in this chapter.

8.1 Small Modular Reactors (SMR)

Passive safety systems (discussed in Chapter 2) are key elements of the state-of-the-art reactor technology, currently under intense development. Another trend is to simplify reactor construction and/or to design small modular reactors, which might be safely operated inside large urban agglomerations. They would be relatively small power reactors capable to be expanded in case the demand for energy has risen.

For many years nuclear power engineers have been striving to build as powerful reactors as practical. The *economy of scale* (belief that both investment and operational unit costs of electricity produced in larger, more powerful units will be smaller than unit costs of electricity produced in smaller units) was the justification. However, a reverse trend has been observed for several years: engineers are now rather talking about small & medium reactors. The supporters of the idea indicate the following benefits:

- Reactor construction may be substantially simplified.
- Reactors might be partly prefabricated in the factory at a significantly reduced cost rather than assembled at the construction site. Various propositions include even an approach, in which an entirely assembled reactor together with its safety containment might be transported from the factory to the site. Of course all constructional and system fitting works will still have to be done at the site.
- Identical modules might be mass-produced at significantly reduced unit costs.
- Less power grids would be necessary. It is more and more difficult task to locate a new power line in any developed country since environment protection regulations are more and more complicated. Medium- and small nuclear power plants located close to the consumers would help to circumvent that problem. US analysts propose premises of old decommissioned coal-fired plants located within city limits as good places to locate SMR nuclear plants.
- Capability to co-generate electricity and heat for district heating systems or for heatintensive industries. Such co-generation might substantially improve economy of the entire plant. Large power plants cannot be used that way since they must be located far from large agglomerations (because of safety reasons). Besides, they usually produce too much heat to be economically consumed by even large industrial plants.

Licensing of such reactors is a separate issue. Traditionally in the past every nuclear facility was separately studied almost from scratch. It took plenty of time and effort. To curb those efforts nuclear regulators in US[21] and UK are considering a new approach, according to which a given reactor type would be licensed rather than each particular

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[20] data published by Japan Ministry of Internal Affairs and Communication, 2013

[21] 10 CFR 52

reactor. Such type certificates would greatly simplify, make more straightforward and less expensive the licensing proceedings, especially in case of SMR reactors.

Let us now have a closer look at several SMR solutions promoted by individual manufacturers.

8.1.1 mPower

In their mPower project Babcock & Wilcox propose to house the reactor itself, steam generator, and pressure stabilizer within a single vertical pressurized tank (Fig.41, similar integration is envisioned also in many other SMR concepts). Steam generator located directly above the reactor core facilitates natural circulation of coolant and helps to carry the decay heat away in any emergency.

Unit power is 180 MWe. The manufacturer proposes to deploy mPower units in pairs each of total power 360 MWe. In locations without sufficient supply of water, mPower reactors could also be cooled down with liquefied air at the price of a smaller output power (310 MWe).

The mPower project has already been supported by US DoE with a 5-year long (2013-2018) $ 150 million grant (another $ 226 million federal funding is expected). Consortium of grantees plan to obtain all necessary permits and to commercially demonstrate the mPower SMR by 2022.

Fig. 41 Babcock & Wilcox mPower unit cross section (source: B&W promotional materials).

Prototype is to be located in Tennessee[22].

8.1.2 NuScale

The NuScale company was called into being to commercialize R&D results obtained in the Oregon State University. Currently it is owned mainly by the Fluor concern. In December 2013 their project to develop a prototype nuclear power plant was supported by a US DoE grant in the amount equal to about 50% of the project budget.

The NuScale design (Fig.42) is very similar to the above described mPower project except for the scale: single much smaller reactor would produce only about 45 MWe. Therefore a group of such reactors would have to be deployed in a single location (NuScale says such a group could consist of even several reactors).

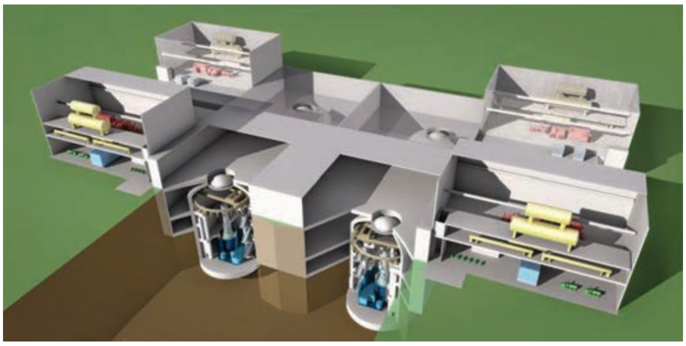

Fig. 41 Babcock & Wilcox mPower unit cross section (source: B&W promotional materials).

Small power of each reactor module offers some advantages. Safety containment with a complete reactor about 4.6 metres in diameter and 25 metres long might be transported from the factory to the construction site on a barge or on a low-floor trailer. That way workload necessary on site could be dramatically reduced.

8.1.3 KLT-40S

Russia has been building small pressurized nuclear reactors (mainly for their submarines, but also for several ice-breakers routinely operating on the Arctic Ocean) for a long time. That know-how has been utilized to design a nuclear power plant located on a floating barge. Prototype of such a barge named *Akademik Łomonosow* (Fig.43) is currently under construction in Murmansk. Operational status of the plant is scheduled for 2016. Target power is 70 MWe. Co-generated heat will be used to heat Pewek, a small town situated in the Chukotka Autonomous Region[23]. That place has been carefully chosen: a mining region located far north in a harsh climate where demand for heat is large while cost of transporting fossil fuel is prohibitively high. Nuclear fuel sufficient for 10 -12 years of operation of the reactor is to be stored on board of the barge.

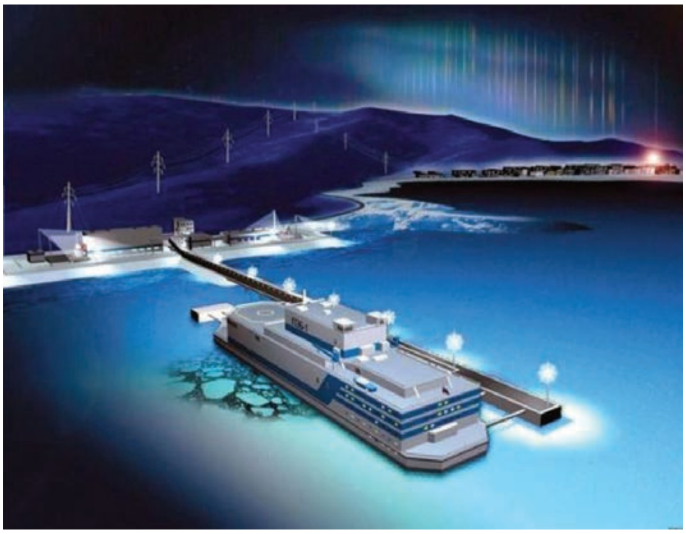

Fig. 43 The "Akademik Łomonosow" barge (source: OKBM Afrikantow promotional materials).

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[22] http://world-nuclear-news.org/NN-SMR_funding_signed_sealed_and_delivered-1604137.html

[23] http://world-nuclear-news.org/NN-Reactors_installed_on_floating_plant-0110134.html

8.1.4 SMART

SMART is a South Korean small PWR reactor with steam generator integrated just like in the mPower and NuScale units. The construction was licensed by Korean Nuclear Regulatory Agency in 2012 (*type certificate*). SMART can co-generate heat (330 MWt) and electricity (100 MWe). A variant in which the reactor powers a seawater desalination plant (90 MWe plus 40 000 m^3 of fresh water per day) is also possible. The project is a joint undertaking of the Korean government and industry. The reactor was to be offered for export to less-developed countries. However, the project has been stalled because of lack of orders[24].

8.1.5 HTR-PM

The HTR-PM high-temperature reactor currently under development in China belongs both to small modular reactors and to 4th generation reactors. Therefore it will be presented in the next section. Here let us say only that its 250 MW thermal power will be converted at 42% efficiency into 105 MW electric power. A common steam turbine is to be powered by a group of six reactors. Currently HTR-PM ranks among the most advanced projects in the field of modular 4th generation reactors.

8.2 4th generation reactors

8.2.1 Introduction: fast reactors and breeders

Neutrons emitted in uranium fission reactions are fast: their energies are of the order of millions electron-volts (MeV). Cross section for absorption of such highly energetic neutrons by other ^{235}U nuclei is too small to sustain chain reaction in conventional uranium-235-based reactors. Therefore fast neutrons must be slowed down in some medium called moderator. Most often normal light water plays the role of the moderator, in some rare cases – graphite. However, reactors based on other than uranium-235 fissile materials may run without any neutron moderator. Three major advantages of fast-neutron reactors (in short: fast reactors) over typical light-water ones include:

- possibility to close the fuel cycle and to produce much more energy from uranium than that obtainable in conventional reactors
- possibility to "burn down" spent fuel used in conventional reactors and that way to limit amount of radioactive waste that has to be stored in underground repositories
- possibility to work at higher temperatures and in consequence to raise efficiency of the turbines.

In spite of these advantages, high investment outlays necessary to develop 4th generation reactors are a problem. Besides, uranium prices are currently rather low and efficient technologies of "burning" uranium are not in demand taking into account that they are also rather costly. Therefore in majority of countries currently fast reactors are perceived as future facilities to burn radioactive waste from conventional reactors down. The issue of better utilization of uranium resources may be placed on the agenda in the future if (and when) uranium prices rise.

The key technical problem with any fast reactor is the cooling medium. Coolant may not slow fast neutrons down (may not simultaneously be a moderator), therefore water is excluded. Various molten metals that may be pumped as any liquid are tried as alternatives. Essential parameters of the most common such alternatives are given in Table 8.1.

Table 8.1 Liquid metals used (or planned) as fast reactor coolants[25]

	Sodium	**Lead**	**Lead-bismuth alloy**
Melting point [°C]	98	327	125
Boiling point [°C]	883	1.745	1.670
Density at 450°C [kg/m^3]	845	10.520	10.150
Specific heat at 450°C [kJ/kg/K]	1.23	0.127	0.128

Can a nuclear reactor produce nuclear fuel? The shortest answer is: YES. Such reactors are referred to as breeders. As a matter of fact, the first power reactor built in 1951 in Idaho (US) was just a breeder. Let us remind that conventional power reactors are ^{235}U-based, while ^{238}U nuclei just absorb or scatter neutrons. However, fast neutrons of energy of the order of 1 MeV may induce fissions of ^{238}U nuclei. Besides, low-energy neutrons may be absorbed by ^{238}U nuclei, in effect producing fissile ^{239}Pu. For that reason ^{238}U isotope is referred to as a *fertile material*[26]. ^{232}Th is another fertile isotope: chain of reactions induced by an absorbed neutron produce in effect fissile ^{233}U. Professionals have high hopes that in the future ^{232}Th may replace uranium as the major nuclear fuel.

Breeders are reactors built to optimize nuclear reactions in which some fissile elements (e.g. ^{239}Pu) are produced. The possibility of producing nuclear fuel as a by-product sounds great, but in reality no currently used power reactor is a breeder. Economic terms are not favourable because (i) rate at which new fuel is produced is rather low; (ii) in the to-day world dominated by uranium-based reactors and at currently low prices of uranium plutonium is of low usability. Nevertheless it is worth to know that modern PWR/BWR reactors utilize only about 1% of energy contained in uranium or thorium, while breeders can utilize almost all that energy. There are some estimates that breeders might supply mankind with electricity for more than 1 million years (at the current energy consumption level and provided that also uranium contained in sea water might be used up). Besides, breeders would be able to effectively "burn down" (i.e. convert to other isotopes) actinides present in spent fuel/nuclear waste. Activity of highly active nuclear waste cleaned of plutonium, americium and curium would drop to a level comparable with activity of natural uranium ores deposited in Earth crust after just about 700 years rather than after 100 000 years as is the case with waste containing the actinides. For technical reasons breeders should preferably be fast neutron reactors.

Three major functions of the breeders envisioned for the future include:

- To produce trans-uranium elements (i.e. elements heavier than uranium[27]) usable as nuclear fuel. Breeders may limit demand for uranium even 100 times in relation to current demand for light water reactor fuel.

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[24] http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Power-Reactors/Small-Nuclear-Power-Reactors/

[25] http://www-pub.iaea.org/MTCD/Publications/PDF/P1567_web.pdf

[26] Of course the ^{238}U isotope remains fertile also in conventional light water reactors. However in such reactors ^{239}Pu is produced at a significantly lower rate that the rate at which ^{235}U is used up.

[27] Every trans-uranium element is simultaneously an actinide.

- To play a role of an isotope converter making possible to balance production and consumption of various trans-uranium elements.
- To convert minor actinides[28] and other long-lived isotopes present in nuclear waste into much shorter-lived isotopes (transmutation).

Potential advantages of fast neutron reactors are accompanied by a few disadvantages: (i) much larger (than in light water reactors) energy density inside the core; (ii) very short lifetime of free neutrons (living from one fission act to another fission act), and (iii) smaller fraction of delayed neutrons (0.35% in comparison to about 0.6% in light water reactors). The disadvantages generally mean that the core must be smaller, temperature in it may change more rapidly, and control circuitry must be able to make a decision to shut the reactor down in a time shorter than 1s. It is indeed a challenge but not any fundamental technical problem.

8.2.2 Sodium-cooled fast reactors (SFR)

8.2.2.1 Introduction

Fast reactors must be cooled down with a medium which neither slow neutrons down nor absorbs them. Mercury – the only metal which is liquid at room temperatures – was the first choice both in US and in the former Soviet Union. Besides, it is a heavy metal that does not slow neutrons down. However, its disadvantages: toxicity for humans, high vapour pressure, and low boiling point (reactor would have to be operated at a relatively low temperature) limited its application to just a few prototypes.

Sodium is an alternative choice. As a light metal it is supposed to somewhat slow neutrons down, but it has got no mercury disadvantages. Melting point 98^{o}C requires that the reactor must be heated during idle time to avoid solidification of sodium inside tubing, but it is just a nuisance. On the other hand sodium's strong reactivity with air and water is a real problem. For that reason every tube and every tank with liquid sodium must have double walls, and space between the walls must be filled up with some inert gas. Some rather complicated leak detectors are necessary. Steam generator is a place where sodium coolant must be close to water to vaporize it into steam needed by the turbine. To limit radiological risks in case of any leak, two sodium loops are necessary: sodium that carries away heat from the reactor core (and contains ^{24}Na radioactive isotope) transfers it to the secondary loop sodium, and only this latter not radioactive medium is allowed into steam generator. All in all, investment costs are high. Two possible solutions are schematically shown in Fig.44.

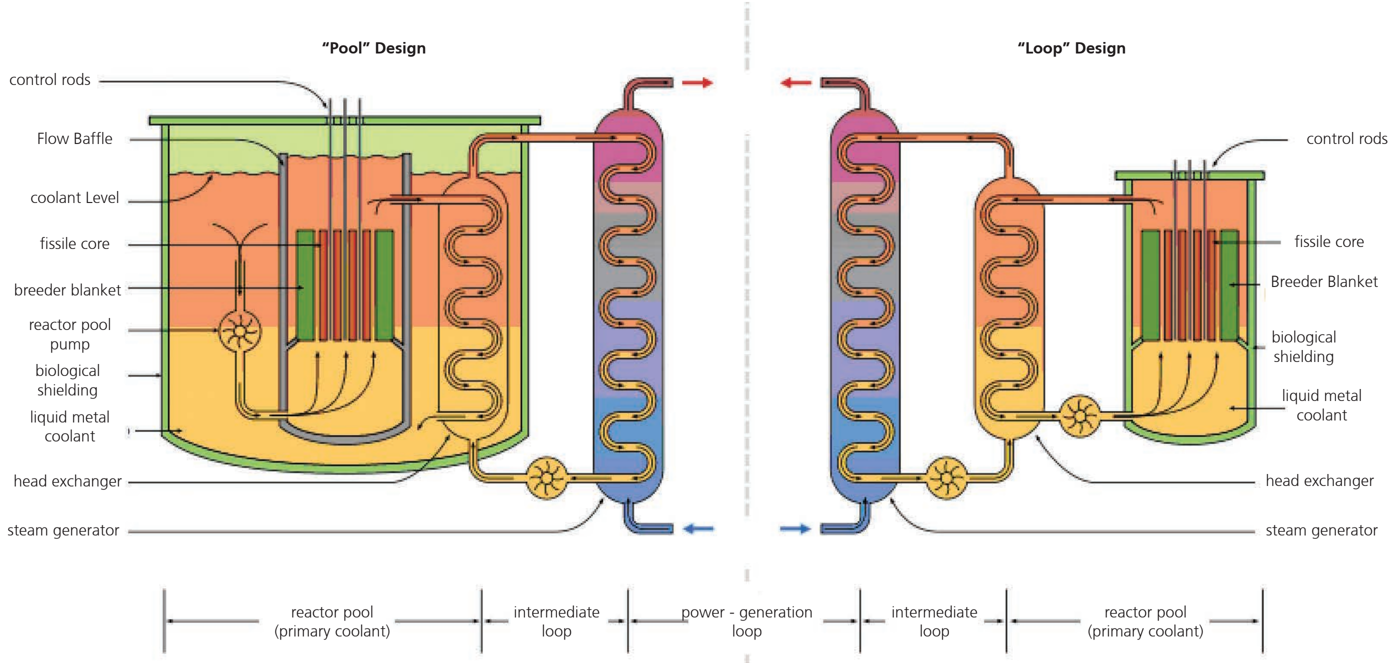

Fig. 44 Two variants of sodium reactor: pool design (left) and loop design (right) (source: Wikipedia Commons).

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[28] All actinides except uranium and plutonium (neptunium, americium, curium, berkelium, californium, einsteinium, fermium).

In the loop design, sodium circulates outside the reactor vessel, although inside biological shield necessary because of the ^{24}Na radioactive isotope. In the pool design, primary heat exchanger and pumps are immersed in the reactor pool. Costs of expensive tubing are reduced in the latter approach, but the pool must be larger.

In spite of all these problems, sodium reactor technology is the most mature among all available technologies of the 4th generation reactors. Several such facilities have already been built and are now tested, works on subsequent facilities of that type are in progress. Approach followed in various countries (USA, France, China, India, Russia, Japan) is briefly presented in subsequent sections.

8.2.2.2 PRISM (USA)

Research on fast reactors has a long tradition in USA. Clementine was globally the first mercury-cooled fast reactor, Fermi-1 was a pilot facility operated between 1969-1972 before the full-scale Clinch River Breeder Reactor Plant project started (never finished because of an unexpected rise of costs and some political issues, just like another later project named Integral Fast Reactor), to name just a few examples. Several research reactors cooled down with sodium or sodium-potassium alloy were also tested.

Drawing on that rich experience GE-Hitachi is currently promoting their PRISM reactor (Fig.45). It is envisioned as a part of a plant built to re-process nuclear fuel spent in conventional light water reactors. Its primary task would be to “burn down” incinerate actinides extracted from the reprocessed fuel, 311 MWe produced power would be a by-product. The remaining waste would contain much less much shorter-lived isotopes.

The PRISM technology is offered for export to a few countries, in particular to UK where stock of plutonium acquired during Cold War times is now a problem.

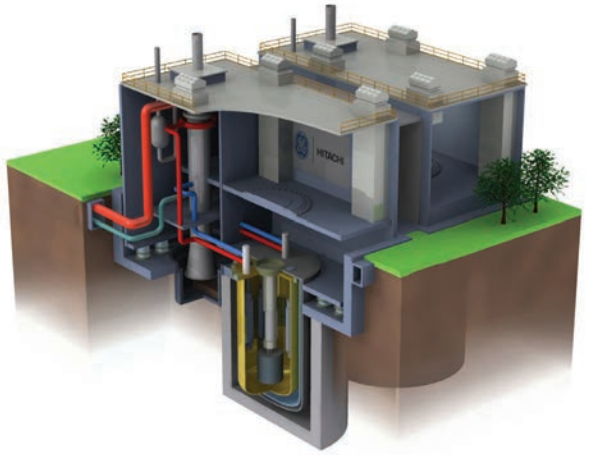

Fig. 45 PRISM (Power Reactor Innovative Small Module) layout, GE Hitachi http://en.wikipedia.org/wiki/S-PRISM.

8.2.2.3 ASTRID (France)

Research on sodium-cooled reactors has a long tradition in France. Rapsodie, the first French reactor of that type (20 MWt) was put in operation already in 1968. Much larger Phenix (140 MWe) was operated between 1973 and 2007. Still larger Superphenix (1 200 MWe), was operated only between 1986 and 1997. That latter project was troubled by some technical problems (sodium leaked, roof over the turbine room fell under the load of snow,…), social protests, legal problems (licence for operation was withdrawn in 1991, it took three years to get a new licence), and finally by low prices of uranium on the world markets in 80’ and 90’. In result reactor was idle longer than worked. The decommissioning decision in 1997 was also a consequence of a French government coalition formed that time with participation of the Greens.

Recently 650 million have been allocated in France for design works on ASTRID (Fig.46), a new 600 MWe fast sodium-cooled reactor. If a decision to build the reactor is made, it should be put in operation around 2020[30].

Fig. 46 Astrid layout.

8.2.2.4 CEFR (China)

20 MWe China Experimental Fast Reactor[31] (CEFR, Fig.47) was connected to the Chinese power grid in 2011. That experimental facility is to verify solutions to be applied in 600 MWe CFR-600 prototype reactor (scheduled for 2023)[32], which in turn is to be followed by 1 000 MWe CFR-1000 commercial reactor (scheduled for 2030)[33].

Fig. 47 CEFR visualisation.

8.2.2.5 PFBR (India)

40 MWt small Fast Breeder Testing facility based on the French Rhapsodie project has been operated in India (Kalpakkam) since the end of ’80. The acquired know-how is currently used to build a much larger (500 MWe) Prototype Fast Breeder Reactor (PFBR). Commercial objects of that type are planned for the future.

8.2.2.6 BN (Russia)

Fast reactors were studied in the former Soviet Union equally intensely as in USA. BR-2, the first mercury-cooled fast reactor, was put in operation already in 1955. It was a very small facility of thermal power just 0.1 MW. Subsequent

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[29] http://www.princeton.edu/sgs/publications/sgs/archive/17-1-Schneider-FBR-France.pdf
[30] http://www.world-nuclear-news.org/NN_Bouygues_joins_Astrid_project_2806121.html
[31] http://www.iaea.org/NuclearPower/Downloadable/Meetings/2013/2013-09-11-09-13-TM-NPTD/7.yang.pdf
[32] https://aris.iaea.org/sites/..%5CPDF%5CCFR-600.pdf
[33] http://www.iaea.org/NuclearPower/Downloadable/Meetings/2013/2013-03-04-03-07-CF-NPTD/5.zhang.pdf

larger facilities (BR-5, BR-10, BOR-60) were already cooled using a sodium-potassium alloy or liquid sodium alone.

125 MWe BN-350 put in operation in 1972 close to Aktau (Shevchenko) in Kazakhstan was the first sodium-cooled power reactor. It was among the most successful sodium-cooled constructions ever. It was producing electricity for almost 20 years, while the produced steam was used to run seawater desalination plant (100,000 m^3 fresh water per day)[34]. However, it was decommissioned when the Soviet Union disintegrated because of large cost of fuel.

BN-600 was the next step. It was put in operation in 1980 and has been reliably operated till now. Different location of the sodium-sodium heat exchangers was the major technological advancement from BN-350 to BN-600: external in respect to the reactor vessel in BN-350 exchangers were in BN-600 moved into the vessel. In result the vessel had to be much larger, but sodium costly tubing could have been greatly reduced (see Fig.44).

Construction of 880 MW BN-800 reactor based on the well proven BN-600 design (Fig.48) started in 1983. Works were halted when the Soviet Union disintegrated, resumed in 2006 in Russia, and currently are approaching the finish[35]. A larger BN-1200 reactor is planned for around 2020.

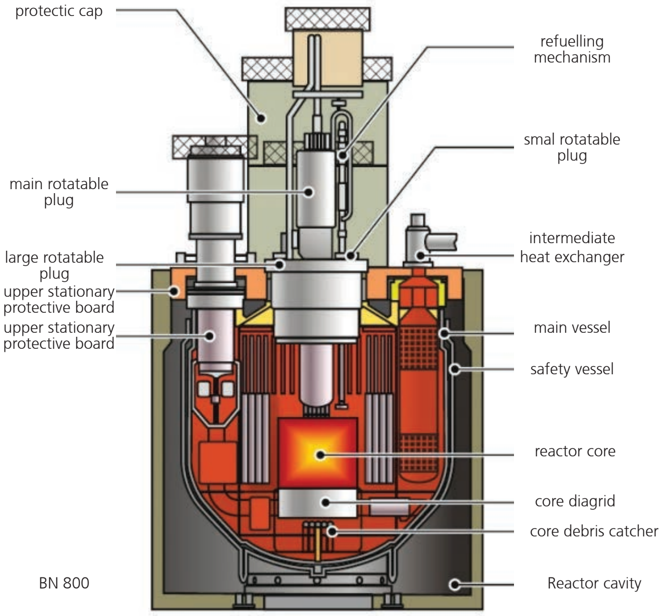

Fig. 48 BN800 layout [36].

8.2.2.7 Japan

Japan was running in the past a rather ambitious programme to develop sodium-cooled breeders. 50 MWt JOYO reactor was put in operation in 1978; its power was later increased to 140 MW[37]. A much larger (280 MWe) MONJU reactor was connected to the power grid in 1995. After failures[38] in 2007 and 1995 currently both reactors are shut down. In view of the current political situation in Japan one should not expect that the Japanese programme to develop fast reactors will soon be continued.

8.2.3 Lead and Lead-Bismuth-Cooled Fast Reactor System (LFR)

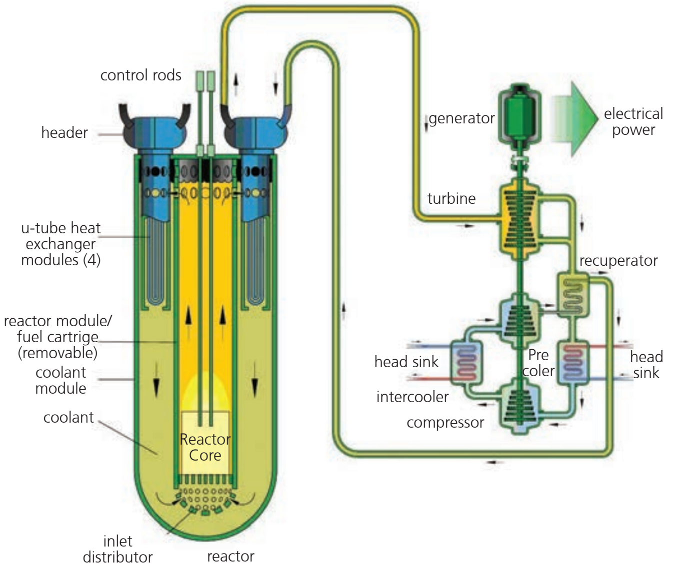

Fig. 49 Lead-or lead-bismuth-eutectic-cooled reactor layout (source: Wikipedia Commons).

Lead-cooled reactors (Fig.49) are an interesting alternative for sodium-cooled reactors since lead is not flawed with the largest sodium disadvantage, namely high reactivity with water. Very high boiling point (1745°C) is another lead advantage: a sodium-cooled reactor might theoretically boil out its coolant in some emergency, while it is practically impossible in case of a lead-cooled reactor.

However, lead has also some very serious drawbacks: (i) is very dense (difficult to pump); (ii) it erodes pump rotors; (iii) its relatively high melting point 327°C needs more heating in idle periods to prevent solidification of the coolant inside tubes/tanks. In that latter respect lead-bismuth-eutectic (44.5% Pb + 55.5% Bi alloy) may be an interesting alternative: its melting point is only 125°C.

Former Soviet Union has been the sole country which practically tried the lead-bismuth-eutectic technology for their submarines. In such applications a possibility to obtain larger power density i.e. smaller reactor sizes compared to conventional PWR reactors[39] is a major advantage. Currently Russians are trying to use the gathered know-how to work out 300 MWe BREST reactor to be located close to Tomsk in Siberia[40].

Less advanced works are conducted also in Europe. MYRRHA lead-bismuth cooled research reactor planned in Mol (Belgium) is also to produce radioisotopes and transmute long-lived isotopes present in spent fuel (we have written more on that project in the first brochure). ALFRED lead-cooled power reactor is planned in Romania (mostly Italian companies are engaged in that project[41]). However, so far neither of those projects has acquired sufficient funding.

Lead cooling technology (and even more lead-bismuth cooling technology) requires a very careful control of coolant contamination level. In particular presence of even residues of oxygen gives rise to corrosion products which accumulate very easily and may quickly clog the coolant channels. It has happened on board of one of Soviet submarines.

Generally lead is a better coolant in power reactors operated most of the time (hence not requiring long periods of external heating) since it is not as demanding in terms of contamination level. The more demanding lead-bismuth eutectic is better in research or military reactors since less energy is required to keep it in the molten state during long stand-by periods.

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[34] http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/28/008/28008858.pdf
[35] http://world-nuclear-news.org/NN-Beloyarsk-4-criticality-soon-3012131.html
[36] http://www.okbm.nnov.ru/npp#regional
[37] http://www.jaea.go.jp/jnc/jncweb/02r-d/fast.html
[38] http://www.iaea.org/NuclearPower/Downloadable/Meetings/2012/2012-06-20-06-22-TWG-NPTD/10_Japan.pdf
[39] http://www.gidropress.podolsk.ru/en/projects/nuclear-submarines.php
[40] http://world-nuclear-news.org/NN_Fast_moves_for_nuclear_development_in_Siberia_0410121.html
[41] http://www.nineoclock.ro/new-type-of-nuclear-reactor-to-be-commissioned-in-mioveni/

8.2.4 Gas-Cooled Fast Reactor System (GFR)

Gas may also be used as fast reactor coolant instead of a liquid metal (Fig.50). Inert helium is the best choice. Advantages of a gas instead liquid metal:

- no corrosion issues
- no coolant activation issues
- reactor core may be easily visually inspected by means of some cameras
- a better neutron balance (helium does not absorb neutrons), therefore waste may be "burned down" with a better efficiency.

Major disadvantages:

- an overpressure must be kept at all times inside the reactor vessel to preserve cooling
- relatively low gas heat capacity in comparison to liquids.

Both disadvantages significantly complicate the task to make the reactor safe.

Two currently considered gas-cooled designs are dubbed EM² (Energy Multiplier Module) and ALLEGRO.

EM² layout is shown in Fig.51. It is proposed by General Atomics, an US company. Reactor fuelled with uranium nitride would be helium-cooled. Hot helium would directly drive a gas turbine.

The ALLEGRO project is based on very similar brief fore-designs. About 70 MWt feasibility demonstrator is planned first. Basic design worked out by French CEA has been handed over for further development to a Hungarian-Czech-Slovak-Polish consortium.

Both projects are currently in their early stages of development and still need plenty of time and effort before they might be implemented. In particular the to-be-solved barriers include the technology of helium driven turbines (some successfully concluded tests cannot be regarded as a proof of a mature technology) and the technology of new fuel materials.

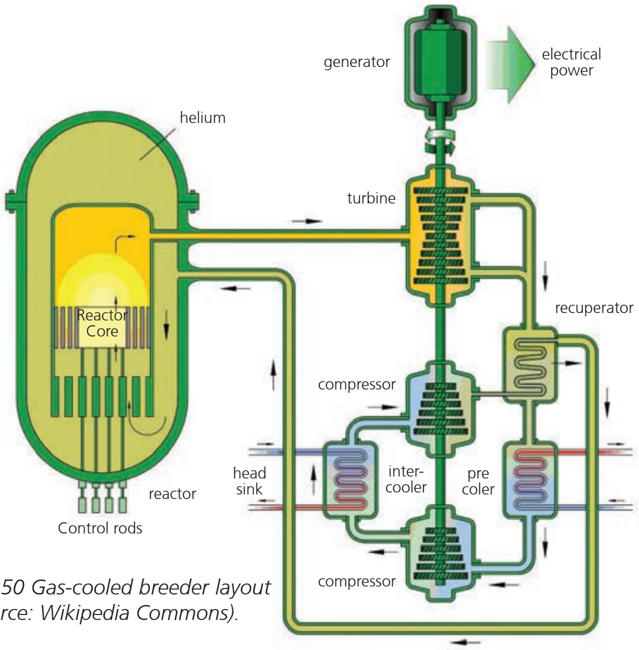

Fig. 50 Gas-cooled breeder layout (source: Wikipedia Commons).

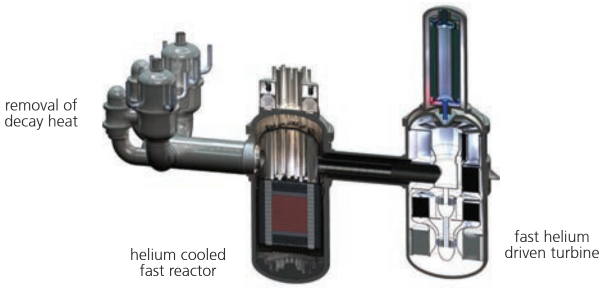

Fig. 51 EM² reactor layout (source: General Atomics promotional materials).

8.2.5 High Temperature Graphite Reactor (HTGR)

Helium is also the coolant of choice in the High Temperature Graphite Reactor approach, but HTGR is not a fast reactor: it uses graphite moderator to slow neutrons down. It is a sole 4th generation reactor employing slow neutrons. The key innovation is related to the fuel: instead of regular rods and pellets, very fine spheres (of diameter of a fraction of one millimetre) each covered with several ceramic layers are planned (Fig.52). Years of experiments resulted in a combination of materials resistant to high temperatures, tight for fission products, and radiation resistant. The technology has been dubbed TRISO.

Introduction of such fuel would flip over the entire nuclear reactor safety philosophy. The entire set of barriers whose task is to prevent release of fission products outside the conventional reactors are here replaced with ceramic coatings covering each individual fuel sphere. The coatings form a kind of "safety containment". Such fuel is resistant to very high temperatures, but requires a very stringent quality control during production to preserve tightness.

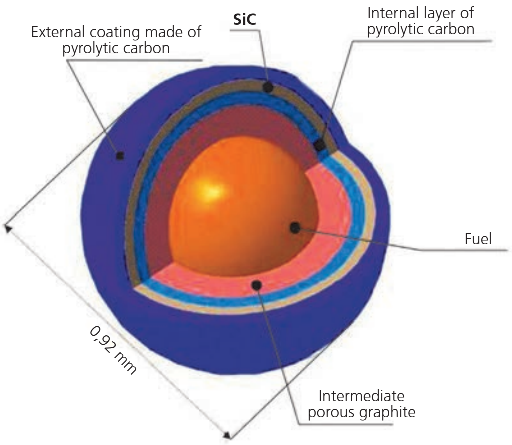

Fig.52 TRISO fuel sphere[42]

HTGR reactor concept was born in Germany and USA, where a few such facilities was operated in the past. A number of technical problems typical for each new technology have been encountered during operation, however none of them was fundamental in nature and/or rose any question about technology feasibility.

Works on HTGR reactors both in Germany and in USA were practically stopped in 80' when low oil prices made investing in new reactor types an economically unjustified venture. Additionally, after the Chernobyl accident, political attitude in Germany became very unfavourable. However, China bought documentation from Germany and a small (10 MW) prototype facility has been operated in Beijing for a few years. Constructional works on a larger facility started in 2012. The HTR-PM (Power Module) facility (Fig.53) will consist of two 250 MWt reactors, each with its steam generator. Helium will be heated up to 750°C, 550°C steam produced by both reactors will drive a single 210 MWe turbine (42% electricity production efficiency). Six-reactor blocks are planned for a more distant future.

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[42] Illustration source: http://www.mpa.fr

The HTR technology has been developed for years also by General Atomics (potentially very attractive Gas Turbine – Modular Helium Reactor combination, in which hot helium would directly drive a helium turbine, see Fig.54, was worked out already at the beginning of 90' but was never implemented); Areva, a French company (their ANTARES project); a consortium of companies from South Korea; and Japanese Atomic Energy Agency (the HTTR prototype 30 MW reactor).

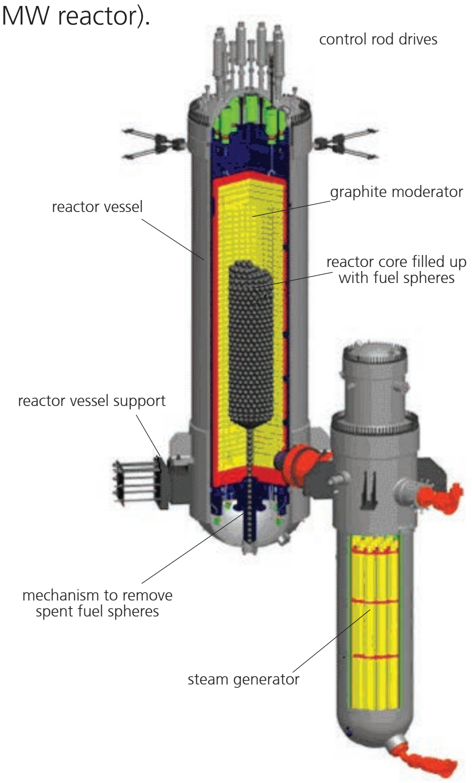

Fig. 53 HTR-PM unit layout (reactor to the left, steam generator to the right). Each fuel sphere (of diameter of about 6 cm) is composed of a few thousand TRISO grains pressed into graphite. Reactor core contains a few hundred thousand such spheres. Source: INET.

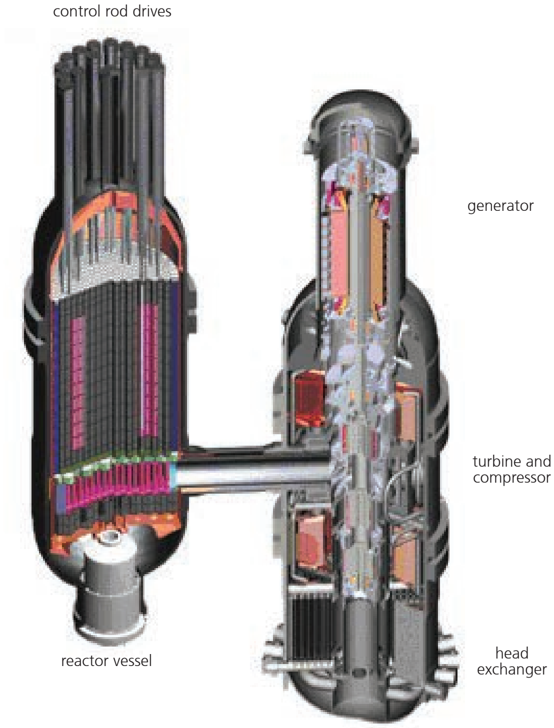

Fig. 54 GT-MHR reactor cross-section.

Safety is an essential advantage of the HTR technology. Reactor vessel is filled up only with some refractory materials (graphite, ceramics), a large graphite mass provides a large thermal inertia so potential incidents run relatively slowly. However, the key feature is capability to release decay heat from the shut-down reactor directly into the atmosphere. Neither complicated cooling systems (of necessarily limited reliability) nor safety containment are required. Large volume reactor vessel (in proportion to the generated power) is its disadvantage.

High helium temperatures make possible energy production efficiency above 40%. Chinese estimate that investment outlays (per 1 MWe) in their HTR-PM technology are comparable to outlays necessary in the PWR conventional technology. High produced temperatures open up applications other than electricity production, supply of industrial heat for large chemical plants in the first place. Such plants usually get the necessary heat from two sources. Fossil-fuel-fired boilers produce steam used in processes running at relatively low temperatures; the steam is also used to preliminary heat up components of processes running at higher temperatures. Each chemical plant is therefore entangled with a web of pipelines supplying steam of various temperatures (usually up to 300°C). Processes requiring higher temperatures are usually supplied with heat by burnt natural gas. In some chemical reactions the gas is simultaneously a substrate (e.g. in production of hydrogen).

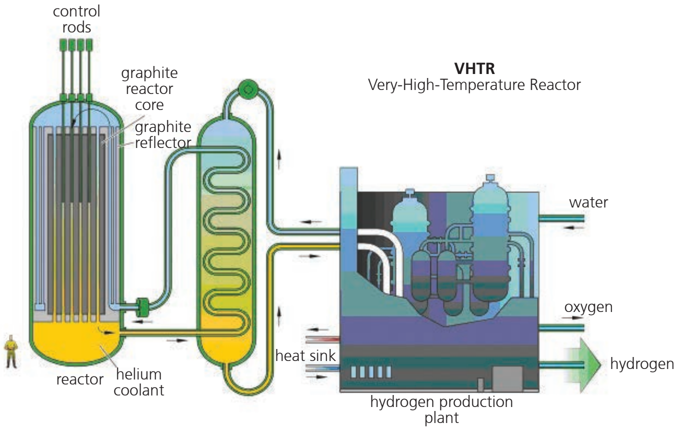

Fig. 55 Layout of a very high temperature reactor that might power up a hydrogen producing plant (source: Wikipedia Commons).

Conventional nuclear reactors may produce steam of temperatures up to 550°C and can replace fossil-fuel-fired boilers as sources of the first type heat. High temperature helium- or molten salt-cooled reactors might replace natural gas as sources of the second type heat provided that chemical plant installations are suitably adopted. The highest helium temperature so far experimentally obtained at the output of AVR reactors in Germany and HTTR reactors in Japan was about 950°C. It was a value close to the limits of modern technology set by strength of materials of which reactor vessel and heat exchangers are made. Therefore the possibility that HTGR reactors will replace natural gas burnt in chemical plants is a distant future perspective. However, national security is here at stake in all countries that must import natural gas. Poland is one of such countries[43].

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[43] https://www.polsl.pl/Wydzialy/RG/Wydawnictwa/Documents/kwartal/5_3_2.pdf

9. COST-EFFECTIVENESS

Nuclear power economics is a difficult subject. Production of electricity to be sold on the market normally should be just a business i.e. a profitable venture. However, state-owned power concerns may sometimes accept loss-making business, provided that the losses are balanced by some benefits for the state, difficult to achieve using other means. National energy independence (or energy security of the country) is the single most important such benefit. However, even such companies do not operate in vacuum and must not depart from market economics too far.

Much has been written on cost-effectiveness of production of electricity from various sources. The drawn conclusions often are contradictory, pointing out competitive edge of one or another selected (supported?) technology. However, some patterns may be identified in various cost comparisons. Levelized Cost of Electricity (LCOE), the most frequently used measure, informs what the price of electricity produced in a given plant should be in order to balance all costs related to the existence of the plant. That figure is by no means related to market price of the energy. It is just an indication at what energy price the plant operator would break even in the entire plant lifecycle.

Let us have a look at individual components of LCOE produced in nuclear power plants.

9.1 Nuclear power costs

9.1.1 Investment outlays (capital cost)

Investment outlays are substantially larger in case of a nuclear power plant than in case of a conventional coal- or gas-fired power plant. Most often development must be financed from a bank loan. Therefore some fraction of the energy price must be set aside for debt service (capital cost).

The outlays may vary depending on local conditions, complexity of the project, efficiency of the contractor etc. In China, where labour is cheap and reactors may be mass-produced, cost of installing one Mega-Watt (electrical) power may be as low as about $2 million. In Europe where accomplishment of the projects is notoriously delayed the cost may exceed $6 million per MWe. Construction time is a very important factor since interest on high amounts invested at the beginning must be paid even if the plant still remains not operational.

Other important factors deciding on capital cost: are (i) loan interest rate; (ii) loan period (at longer periods instalments payable each year are less, but total sum of the to-be-paid interest is larger). Operational costs of a plant for which the entire loan has already been repaid may dramatically drop down.

Share of the capital cost in energy price will be the lower, the more energy is produced by the given plant. For that reason any longer plant shut downs are costly and operators try to avoid them as much as they can. Sample results of calculations of that share depending on interest rate, credit repayment time, duty factor, construction costs) are shown in Table 9.1. The data illustrate how sensitive capital costs may be for quite limited changes of variables.

Table 9.1 Share of capital cost in energy price

Factor	Unit of measure	Variant	
Construction costs	$ million / MWe	4	6
Duty factor	%	90	70
Loan interest rate	%p.a.	4	8
Loan period	years	30	20
Share of capital cost in price of each kWh	US¢ / kWh	4	9

As can be seen, capital cost is a major energy price factor. Financing conditions may critically impact evaluation of profitability (hence: purposefulness) of any given project. That is the reason why state-owned entities dominate among operators of nuclear power plants: they are just able to receive credit on better conditions.

9.1.2 Fixed costs

These are costs born regardless whether the given plant is or is not operated: staff remuneration, energy to light up/heat the premises, regular maintenance inspections etc. Just like in case of capital cost, share of the fixed costs in the energy price will be the lower, the more energy is produced by the given plant.

9.1.3 Variable costs

These are costs related to physical operation of the plant e.g. cost of replacement of wearable elements. Fuel costs are basically also variable costs, but we will discuss them separately.

9.1.4 Fuel costs

Nuclear fuel – just like uranium ores necessary to manufacture the fuel – is typically supplied on a basis of some long-term contracts and its price does not fluctuate much. Several vendors compete worldwide since in view of relatively very low transport cost none of them is able to monopolize the market. US data show that fuel share in LCOE was $0.75 US¢ / kWh[44] in 2012, including waste management costs, see below.

9.1.5 Waste management costs

The most simple solution is to bury spent fuel in some deep underground yard. It may be a costly venture to build such a final storage repository since (i) extremely comprehensive environmental research is necessary before a permit to locate such a repository is obtained, and (ii) deep tunnels must be bored. The place must be devoid of ground waters, the single largest risk factor that in the distant future waste containers will corrode and the buried waste will be released to the environment. Yucca Mountain desert area in Nevada has already been accepted in the US as the repository location. Unfortunately, later political games resulted in cancellation of the entire project. There is no other long-term solution in the US[45].

However, we are here interested in costs, and these have been partly borne, partly well estimated during the time the project was under accomplishment. Total costs of constructing, operating for 150 years and decommissioning the repository were in 2008 estimated for $96 billion. 80% of that cost was to be covered by a tax imposed on nuclear power plant operators in the amount of US˘ 0.1 / kWh[46].

[44] Data from the Nuclear Energy Institute webpage

[45] In the final storage sense; spent fuel temporary storage is a different thing

[46] http://www.world-nuclear-news.org/W7R-Yucca_Mountain_cost_estimate_rises_to_96_billion_dollars-0608085.html

About 100 nuclear power reactors are currently operated in the US. However, even if scale economies are not as favourable in smaller countries, nuclear waste management costs are just a few percent of the total fuel cost.

9.1.6 Plant decommissioning costs

Nuclear facility decommissioning costs may be substantial. Therefore Polish law (just like law in many other countries) requires the operators to put aside each month about US¢ 0.4/kWh to a dedicated plant decommissioning fund.

Contrary to the capital costs case, here time is working in favour of the plant operator. The decommissioning procedures may be delayed even by several tens of years after the plant is shut down to wait until activity of radioactive contaminants accumulated within the plant buildings drops down, while the decommissioning funds may in the meantime earn interest. On the other hand even shut down but not decommissioned plant legally remains a nuclear facility that must be guarded round the clock, and the land plot occupied by it may not be utilized for other purposes.

Unless (i) the decommissioning fund was never accumulated as in case of the old Magnox reactors in UK, decommissioning of which is now a financial challenge; (ii) plant was shut down very early because of some failures or revealed drawbacks; or (iii) national economy broke and the decommissioning fund went bankrupt – even a very small premium paid regularly is enough to cover all decommissioning costs. If the latter costs are equal to 50% of construction costs, the plant is operated for 60 years, and interest on deposits is 6% p.a. share of the necessary decommissioning premium in LCOE may be roughly estimated for about US¢ 0.05/kWh, a completely insignificant factor compared to other costs.

9.2 Comparison with other types of power plants

We are not going to discuss here any detailed figures but rather to present some general dependencies and trends.

9.2.1 Gas-fired plants

Such plants are relatively cheap to construct but expensive to operate in view of high gas prices. In Poland, natural gas costs about US¢ 35/m^3. At that price fuel itself would contribute about US¢ 6.5/kWh to LCOE. CO_2 emission licence fees in Europe were not known at the time this text was written.

9.2.2 Coal-fired plants

Such plants are somewhat more expensive to construct than gas-fired ones. Two examples from Poland: (i) each MWe installed in currently developed units of the 2 x 900 MW Opole Power Plant is going to cost about $1.1 million. (i) each MWe installed in currently developed 1 075 MW unit of the Kozienice Power Plant is going to cost about $1 million.

On the other hand, cost of the fuel (coal) is quite low, currently about US¢ 2.5/kWh. Coal-fired plants emit about twice as much CO_2 as gas-fired plants. However, in Poland emission licence fees are required only for newly constructed power generation units – old units are exempt.

9.2.3 Wind farms

In Poland, each Megawatt of wind farm power costs about $1.6 million, i.e. relatively not much. However, because of wind variability, wind farm duty factor rarely exceeds 25%. It means that most of the time such farm is operated at a fraction of its rated (installed) power. In consequence, share of the capital cost in LCOE may be pretty high. At development costs $1.6 million/MWe, duty factor 22%, 20 year loan granted at 6% p.a. that share will be about US¢ 7/kWh. At present sustainable energy sources (including wind farms) are heavily subsidized by many European governments (preferential credits, guaranteed prices and similar mechanisms).

Off-shore wind farms reach higher duty factors (up to 40%), but their construction costs are significantly higher.

Once share of wind-farm-generated power in national power system exceeds some level, a significant problem becomes visible: it is wind farm output power variability. Electric energy with national power system may not be easily stored (except for small pumped storage power plants) so in principle instantaneous supply must always follow instantaneous demand. Operator of the national power system must react to variability introduced by wind farms by turning reserve power sources on and off, which not always is a straightforward task. More reserves kept stand-by mean also higher costs.

9.2.4 Photovoltaic farms

Photovoltaic farms have all drawbacks of wind farms, their duty factor (in Polish climate) is even smaller, just several percent. Their costs are currently even higher than wind farm costs. Without heavy government subsidies that source of power – as the most expensive among competitors – would be non-existent (except for special cases).

On the other hand it cannot be overlooked that photovoltaic technology has been advancing very rapidly and prices of photovoltaic panels are constantly dropping down. Supporters of that technology also indicate that daily peaks in demand for electricity overlap to some degree with daily peaks in solar power. Therefore, photovoltaic farms are better suited to "friendly" cooperate with national power degrees that wind farms are.

10 SUMMARY

Obviously, we were not able to exhaustively discuss in this brochure all questions concerning nuclear power. However, the brochure – in tandem with our previous "Nuclear power: the first encounter" brochure – may be treated as a compendium of basic knowledge on the subject.

To-day it is difficult to tell which of numerous concepts of new reactor technologies will in future join portfolio of proven solutions applied on a regular basis by power generation industry, and what new ideas – particularly on reactor safety and on waste management – will be brought by the future.

A objective to efficiently burn down spent fuel in order to substantially decrease amount/activity of the currently accumulated waste (and to generate electricity by the way) seems to be within our reach in not-so-distant future. Already current nuclear power is in fact quite environment-friendly, but attaining the above objective would make it even more efficient and much easier to accept by societies.

In our brochures we have been pointing out many times that ionizing radiation emitted by a normally operated nuclear power plant is so low that it can in no way harm people living in the plant vicinity. Modern reactor designs guarantee also that no consequences of any typical failure will be felt within a zone around the failed reactor of about 1 km radius. No resettlement of inhabitants (as was the case in Chernobyl and Fukushima) will ever have any sense. Reactor safety became an utmost issue: quality control during reactor construction and operation became extraordinary stringent, very improbable worst case failure scenarios have been considered and respective safety measures introduced. After the Fukushima accident all older reactors still in operation worldwide have been stress-tested and safety measures have been improved where applicable.

Our previous brochure may have left the Readers asking themselves a question whether the course towards nuclear power is a proper course. We hope that this brochure has cleared any doubts. Nuclear power is safe, environment friendly, affordable for electricity/heat consumers. The technology is capable to provide mankind with clean energy for at least tens of thousands of years. What else could you possibly want?

11. GLOSSARY

ABWR
Advanced Boiling Water Reactor. Reactor worked out in 80'/90', currently offered for sale by General Electric, Hitachi, and Toshiba. A few such facilities are operated in Japan, other are currently under construction on Taiwan.

AGR
Advanced Gas Cooled Reactor. British reactor of 2nd generation evolved from the 1st generation Magnox reactors.

AP1000
Advanced Passive 1000. PWR-type reactor of power 1 000 MWe, currently offered for sale by Westinghouse. A few such facilities are currently under construction in USA and China.

BN350, BN600, BN800, BN1200
Russian family of sodium cooled fast reactors of power 350/600/800/1,200 MWe, currently shut-down/operated in Biełojarsk/under development/under design, respectively.

BWR Boiling Water Reactor. One of two major types of conventional power reactors.

CANDU
CANadian Deuterium Uranium. Canadian family of PHWR-type reactors exported to India, Pakistan, Romania, South Korea, Argentina, China.

EM2
Energy Multiplier Module. Helium cooled fast reactor project promoted by the General Atomics company (San Diego, Ca, USA).

ESBWR
Economic Simplified Boiling Water Reactor. BWR-type reactor of a new generation, offered for sale by General Electric/Hitachi consortium,

GT-MHR
Gas Turbine Modular Helium Reactor. HTR-type reactor/helium turbine combination project worked out in 90' by General Atomics.

HTR
High Temperature Reactor. Helium cooled reactor with graphite moderator.

HTGR
High Temperature Graphite Reactor. US equivalent for HTR, used to distinguish such reactors from other technologies also capable to produce high temperature heat.

HTR-PM
HTR-Power Module. Chinese use that name for two HTR-type reactors currently under development in China.

IAEA
International Atomic Energy Agency. UN agency promoting peaceful applications of nuclear energy and preventing proliferation of nuclear weapons.

INES
International Nuclear Event Scale

Magnox
Magnesium, non-oxidizing. Magnesium alloy used for cladding of fuel applied in 1st generation British CO_2 cooled reactors. Commonly used name for all those reactors.

MW
Megawatt. Unit of power.

MWe
Megawatt of electric power. Unit of electric power.

MWt or **MWth**
Megawatt of thermal power. Unit of thermal power.

MWh Megawatt hour. Unit of energy.

PHWR
Pressurized Heavy Water Reactor. Reactor type similar to PWR, but heavy water rather than ordinary light water is used as the moderator and coolant. The type popular in Canada (CANDU) and India (licenced by Canadians).

PWR
Pressurized Water Reactor. One of two major types of conventional power reactors.

RBMK
In Russian: Large Power Channel Reactor. Soviet reactor type with moderator graphite, cooled by pressurized boiling water. Never offered for export since it is capable to produce military-grade high purity plutonium. Chernobyl power plant employed just such reactors. Currently RBMK reactors located in Lithuania and Ukraine are shut down, a few RBMK reactors are operated exclusively in Russia.

TMI
Three Mile Island. Power plant in Pennsylvania (USA). One of the two PWR-type Babcock&Wilcox reactors installed in that plant failed in 1979. It was one of the few famous accidents in history of civil nuclear power.

TSO
Technical Support Organisation. A body with scientific/technical potential in the field of nuclear power technologies necessary to deliver expert services, to conduct R&D works, to verify not yet checked technical solutions etc. In some countries TSOs are parts of Nuclear Regulatory Agencies, in others – independent organizations that may be hired by Nuclear Regulatory Agencies or nuclear industry.

WANO
World Association of Nuclear Operators

WWER
In Russian: Water-Water Power Reactor. Soviet family of PWR-type reactors exported to many countries including former east bloc countries, India and Iran. Power of the most popular variants is 440 and 1 000 MWe.

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