PRVIH POLA STOLJEĆA KOMERCIJALNIH NUKLEARNIH ELEKTRANA

THE FIRST HALF CENTURY OF COMMERCIAL NUCLEAR POWER PLANTS

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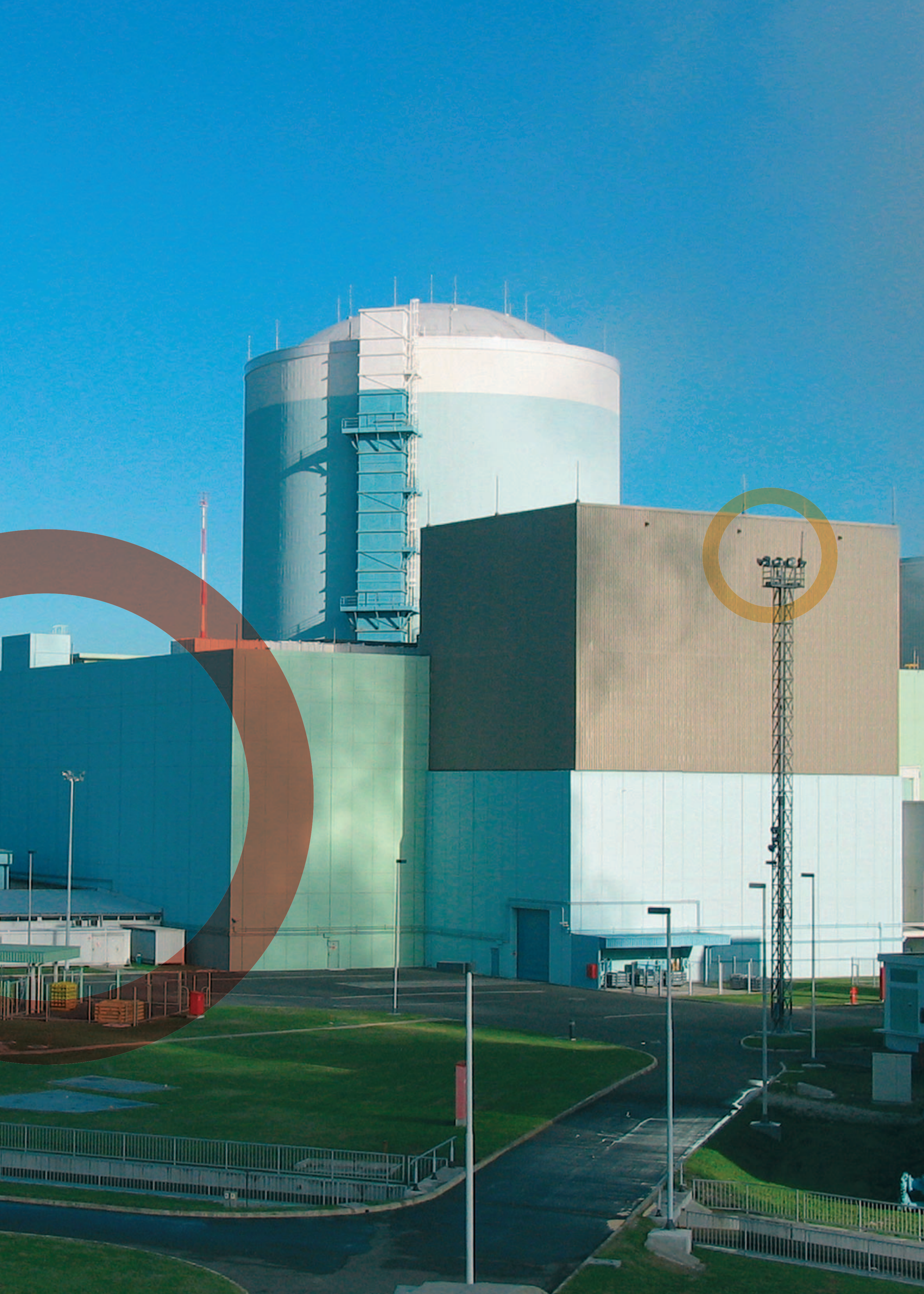
Nakon pet desetljeća postojanja nuklearna energetska industrija je sazrijela, a njen udio u opskrbi električnom energijom na svjetskoj razini je 16 %. Članak daje pregled polustoljetnog razvoja nuklearne tehnologije s naglaskom na miroljubivu primjenu. Okolnosti razvoja i kasnijeg pada korištenja nuklearne energije analiziraju se s više aspekata. Opisuju se karakteristike četiri generacije nuklearnih reaktora, dostatnost rezervi urana kao nuklearnog goriva, problematika zbrinjavanja radioaktivnog otpada te pitanja sigurnosti i ekonomičnosti pogona i proliferacije nuklearnih materijala. Analiziraju se glavne prednosti i nedostatci nuklearne energije u svjetlu najava o značajnom proširenju nuklearnih kapaciteta

After five decades that the nuclear power industry has been in existence, it has matured and its share in the world energy supply is 16 %.The article provides a review of the development of nuclear technology during the past half century, with emphasis upon peaceful applications. The circumstances of the development and subsequent decline in the demand for electricity from nuclear power plants are analyzed from several aspects. The characteristics of the four generations of nuclear reactors, the sufficiency of the uranium reserves and nuclear fuel, the problem of the disposal of radioactive wastes, the safety and cost-effectiveness of nuclear power plants, and the proliferation of nuclear materials are also discussed. The chief advantages and disadvantages of nuclear energy are analyzed in light of statements on the significant expansion of nuclear capacities.

Ključne riječi: nuklearna sigurnost, nuklearne elektrane, nuklearno gorivo, proliferacija, radioaktivni otpad
Key words: nuclear fuel, nuclear power plants, nuclear safety, proliferation, radioactive waste



1 UVOD

Kroz gotovo četiri desetljeća nizala su se razna otkrića vezana uz ionizirajuće zračenje i strukturu tvari, da bi 1939. Otto Hahn i Fritz Strassman u Berlinu proveli eksperiment u kojem su uz pomoć Lise Meitner otkrili fisiju – cijepanje težih jezgri uz oslobađanje velikih količina energije. Temeljem tih istraživanja, tri godine kasnije Enrico Fermi konstruirao je prvi nuklearni reaktor sa samoodržavajućom fisijom. Svijet je ušao u atomsko doba.

Kroz idućih pet i pol desetljeća nuklearna tehnologija doživjela je značajan razvoj i različite primjene. U tom je razdoblju prolazila kroz razdoblja velikih očekivanja, ali i velikih razočaranja. Danas ponovno izgleda da nuklearna tehnologija može ponuditi odgovore na energetske probleme.

U proteklim godinama pokazale su se sve prednosti, ali i svi nedostaci ove tenologije, a o njoj se i danas, kao o rijetko kojoj temi, još uvijek vode brojne, žučne polemike

U ovom će se radu biti dan pregled najvažnijih aspekata razvoja nuklearne industrije i okolnosti u kojima se on zbivao.

2 DRUŠTVENE I POLITIČKE OKOLNOSTI RAZVOJA

Razvoj nuklearne tehnologije od samih početaka pobudio je velik interes, kako znanstvenih, tako i vojnih i političkih krugova. S obzirom na ratno vrijeme u kojem se odvijao, nova su otkrića prvu primjenu dobila u atomskoj bombi. Nažalost, tragedije Hiroshime i Nagasakija već 60 godina prate razvoj miroljubive primjene nuklearne energije.

Razvoj nuklearne energetike i nuklearne industrije u poslijeratnom razdoblju bio je i dalje obilježen vojnom primjenom nuklearne energije. Tako su u poslijeratnom razdoblju mnoge države razvijale nuklearne energetske programe samo kao komplement vojnim programima.

Prekretnicu u korištenju nuklearne energije iz vojnih u energetske svrhe označio je govor tadašnjeg predsjednika SAD-a, D. Eisenhowera, koji je 1953. godine pred Ujedinjenim narodima održao govor Atomi za mir. Tri godine nakon toga prva komercijalna nuklearna elektrana Calder Hall počela je proizvoditi nuklearnu energiju. Privatne tvrtke su uvidjele mogućnosti nove tehnologije te su se počele sve više uključivati u razvoj

1 INTRODUCTION

Over a period of nearly four decades, there were various discoveries connected with ionizing radiation and the structure of matter. In 1939, Otto Hahn and Fritz Strassman, with the help of Lise Meitner, conducted an experiment in Berlin through which they discovered fission – the splitting of heavy nuclei with the liberation of large amounts of energy. Based upon these investigations, three years later Enrico Fermi constructed the first nuclear reactor with self-sustaining fission. The world had entered the Atomic Age.

During the subsequent five and a half decades, nuclear technology underwent significant development and various applications, with great expectations and great disappointments. Today it again appears that nuclear technology can provide answers to energy problems.

During the past years, all the advantages and shortcomings of this technology have become apparent, although polemics on the subject continue.

This article will review the most significant aspects in the development of the nuclear industry and the surrounding circumstances.

2 THE SOCIAL AND POLITICAL CIRCUMSTANCES OF DEVELOPMENT

From the very beginning, the development of nuclear technology aroused great interest among scientific, military and political circles. Since this development occurred during wartime, the new discoveries were initially applied to the atomic bomb. Unfortunately, the tragedies of Hiroshima and Nagasaki have cast a shadow on the development of peaceful applications of nuclear energy for the past 60 years.

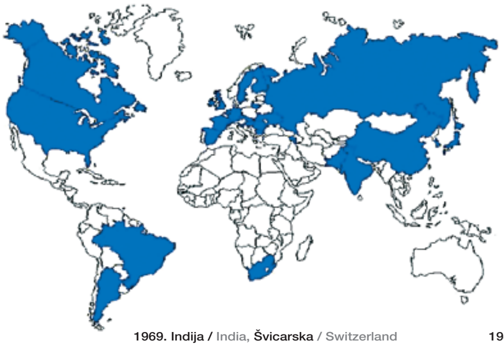
The development of nuclear energetics and the nuclear industry following the Second World War was further characterized by the military applications of nuclear energy. Thus, many countries during the postwar period only developed nuclear energy programs as a complement to their military programs.

The turning point in the use of nuclear energy from military to energy purposes was a speech by United States President Dwight D. Eisenhower in 1953 before the United Nations, in which he spoke about atoms for peace. Three years later, the first commercial nuclear power plant, Calder Hall, began to produce nuclear energy. Private companies saw opportunities in the new technology and began komercijalnih nuklearnih reaktora. Očekivanja od nuklearne industrije bila su velika, a poslijeratno raspoloženje javnosti odražavalo je vjeru u mogućnosti znanosti i novih tehnologija.

Predstavnici nuklearne industrije su, i sami poneseni spektakularnim rastom, mnogo obećavali. Tako je Lewis L. Strauss, predsjedavajući Komisije za atomsku energiju 1954. godine izjavio da je realno očekivati da će naši potomci uživati u električnoj energiji toliko jeftinoj da je se neće isplatiti naplaćivati.

to be increasingly involved in the development of commercial nuclear reactors. The expectations from the nuclear industry were great and the postwar public mood was positive toward the possibilities of science and new technologies.

Representatives of the nuclear industry, themselves carried away by the spectacular growth, promised much. Thus, Lewis L. Strauss, chairman the Atomic Energy Commission, announced in the year 1954 that it was realistic to expect that our descendents would enjoy such inexpensive electricity that it would be "too cheap to meter."



Slika 1
Zemlje koje danas imaju komercijalne nuklearne reaktore i vrijeme puštanja u pogon prvih komercijalnih nuklearnih postrojenja [1].
Figure 1
Countries with commercial nuclear reactors today and the years when the first commercial nuclear power plants went on line [1]

1954. Rusija / Russia
1956. Velika Britanija / UK
1957. SAD / United States
1958. Francuska / France
1961. Njemačka / Germany
1962. Belgija / Belgium, Kanada / Canada
1963. Italija* / Italy, Japan / Japan
1964. Švedska / Sweden
1968. Nizozemska / Netherland, Španjolska / Spain
1969. Indija / India, Švicarska / Switzerland
1971. Pakistan / Pakistan
1972. Slovačka / Slovakia
1973. Kazahstan* / Kazakhstan
1974. Argentina / Argentina, Bugarska / Bulgaria
1975. Finska / Finland
1976. Armenija / Armenia
1977. Koreja / Korea, Ukrajina / Ukraina
1981. Slovenija / Slovenia
1982. Brazil / Brasil, Mađarska / Hungary
1983. Litva / Lithuania
1984. JAR / RSA
1985. Češka / Chech Republic
1989. Meksiko / Mexico
1991. Kina / China
1996. Rumunjska / Romania

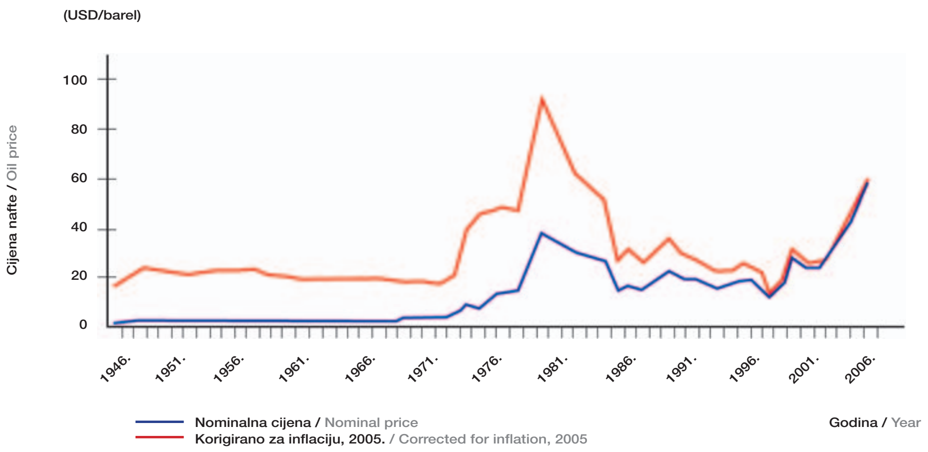
*Italija i Kazahstan zatvorili su svoje nuklearne elektrane 1990. i 1999. godine / Italy and Kazakhstan closed their nuslear power plants in 1990 and 1999

S druge strane je pokroviteljstvo države i paralelno razvijanje vojnih programa u značajnom dijelu javnosti produbljivao animozitet prema nuklearnoj energiji. U nadolazećim godinama taj će uteg postati pretežak za nuklearnu energetsku industriju.

Veliki poticaj razvoju nuklearne industrije dala je i naftna kriza 1973. godine (slika 2), te kasnije krize u Iranu koje su uzrokovale skokovite poraste cijene nafte, te natjerale države da energetsku neovisnost postave kao jedan od prioriteta energetske politike.

From the other side, state sponsorship and the parallel development of military programs significantly heightened public animosity toward nuclear energy. In coming years, this burden would become too heavy for the nuclear power industry.

Great incentive to the development of the nuclear power industry was provided by the oil crisis of 1973 (Figure 2), and later the crisis in Iran that caused great increases in oil prices and forced countries to place energy independence among their priorities in energy policy.



Slika 2
Povijesno kretanje cijena nafte [2]
Figure 2
Historical trends in oil prices [2]

U proljeće 1986. godine u ukrajinskoj elektrani Černobilj došlo je do zloglasne nesreće na reaktoru IV. Tridesetak osoba, uglavnom vatrogasci koji su sanirali požar na reaktoru izgubilo je živote neposredno nakon nesreće, čitava okolna naselja s ukupno 350 000 stanovnika su evakuirana i preseljena, a procjenjuje se da je do danas od posljedica te nesreće živote moglo izgubiti do 4 000 ljudi [3]. Taj je događaj bio prekretnica daljnjeg razvoja nuklearne industrije. Za percepciju javnosti na Zapadu nije mnogo značilo uvjeravanje nuklearnih pobornika da u zapadnim elektranama takva nesreća nije moguća, prvenstveno zbog značajnih razlika u dizajnu same elektrane. Černobilska katastrofa postala je gotovo sinonim za nuklearnu energiju. Uz to je zbrinjavanje radioaktivnog otpada nagomilanog iz desetljeća rada elektrana javnost prepoznala kao još uvijek neriješen problem. U to vrijeme nuklearna industrija nije imala spreman uvjerljiv i adekvatan odgovor na pitanja sigurnosti i zbrinjavanja otpada.

Nakon katastrofe u Černobilju nuklearke postaju neprijatelj broj jedan za gotovo sve organizacije zelenih u svijetu. Biti protiv bilo je *in*. To je prisililo vlade zapadnih zemalja da počnu odustajati od daljnjeg razvoja svojih nuklearnih programa, pa čak i napuštati nuklearnu tehnologiju kao izvor električne energije. Tako je Austrija 1978. godine donijela zakon kojim se zabranjuje uporaba nuklearne energije za proizvodnju električne energije i odustala od stavljanja u pogon potpuno dovršene elektrane Zwentendorf. Italija je 1990. godine prije isteka životnog vijeka trajno obustavila rad i posljednjeg od svoja četiri nuklearna reaktora, dok su Njemačka i Švedska odlučile postupno smanjiti broj svojih nuklearnih reaktora.

In the spring of 1986, an accident occurred in Reactor No. 4 at the Ukrainian nuclear power plant in Chernobyl. Approximately thirty persons, mainly firefighters and rescue workers who sanified the fire in the reactor under control, lost their lives directly after the accident. The entire surrounding community of 350 000 inhabitants was evacuated and relocated, and it is estimated that up to 4 000 persons could have lost their lives to date from the consequences of this accident [3]. This event was the turning point in the further development of the nuclear industry. In the perception of the Western public, the assurances of nuclear supporters that such an accident would be impossible in Western nuclear power plants, first of all due to the significant differences in the designs of the power plants themselves, did not matter much. The Chernobyl catastrophe became practically synonymous with nuclear energy. Moreover, the disposal of radioactive wastes that accumulate after decades of nuclear power plant operation has been recognized by public opinion as a problem that remains unsolved. At the time, the nuclear industry did not have a convincing and adequate response prepared to the questions of safety and waste disposal.

Following the Chernobyl catastrophe, nuclear power plants became Public Enemy No. 1 for all the green organizations in the world. To be against nuclear power was *in*. This forced the governments of Western countries to begin to refrain from the further development of their nuclear programs, and even to abandon nuclear technology as a source of electricity. Thus, in 1978 a law was adopted in Austria which prohibited the use of nuclear energy for the production of electricity and prevented the completed Zwentendorf Nuclear Power Plant from going on line. In 1990, Italy terminated the operations of the last of its four nuclear reactors before its working lifetime had expired, while

Prirodni plin postao je najpoželjniji energent budućnosti u mnogim državama. Tako je udio prirodnog plina u periodu od 1992. do 2003. godine u europskoj energetskoj bilanci porastao sa 6 % na 18 %, tj. njegova potrošnja za proizvodnju električne energije povećana je više od 3,5 puta [4].

Efekt staklenika uzrokovan antropogenim emisijama u atmosferu identificiran je kao prioritet u globalnim naporima za očuvanje okoliša i približavanje konceptu održivog razvoja. Obovljivi izvori energije nudili su se kao rješenje, kako za pitanje zaštite okoliša, tako i za pitanje sigurnosti opskrbe. Kao nužnost, prepoznate su i mjere štednje energije i energetske efikasnosti.

Danas, dva desetljeća od Černobilja i pet desetljeća od Calder Halla, situacija se ponovno mijenja. Velik porast potražnje za prirodnim plinom u Europi uzrokovao je probleme u opskrbi i snažan rast njegove cijene, a prošlogodišnje redukcije u isporuci ruskog plina pomogle su mnogim europskim državama spoznati posljedice pretjerane energetske ovisnosti. S obzirom na predviđeni porast potrošnje električne energije, očekuje se da će do 2012. godine u Europi biti potrebno izgraditi najmanje 65 GW novih kapaciteta. Sudeći prema najavama, taj kapacitet će većim dijelom biti plinske elektrane što znači da će godišnji uvoz plina u Europu sa sadašnjih 230 milijardi kubnih metara do 2012. godine morati narasti na najmanje 465 milijardi kubnih metara [4].

Unatoč velikim ulaganjima u obnovljive izvore energije (biomasa, hidroenergija, energija vjetra, Sunčeva energija i geotermalna energija) njihov udio u zadovoljenju ukupnih energetskih potreba je još uvijek marginalan, tek oko 6 % na razini Europske unije, koja je predvodnik u korištenju obnovljivih izvora. Posljedice efekta staklenika prepoznate su kao stvaran i vrlo aktualan problem te izgleda da i zeleni polako prihvaćaju da obnovljivi izvori i energetska efikasnost, iako korisni, ne mogu pružiti rješenje na globalnoj razini, niti ga mogu pružiti dovoljno brzo, naročito s obzirom na golem porast potražnje za energijom koju bilježe ekonomije zemalja u razvoju, posebice Kine i Indije (slika 3).

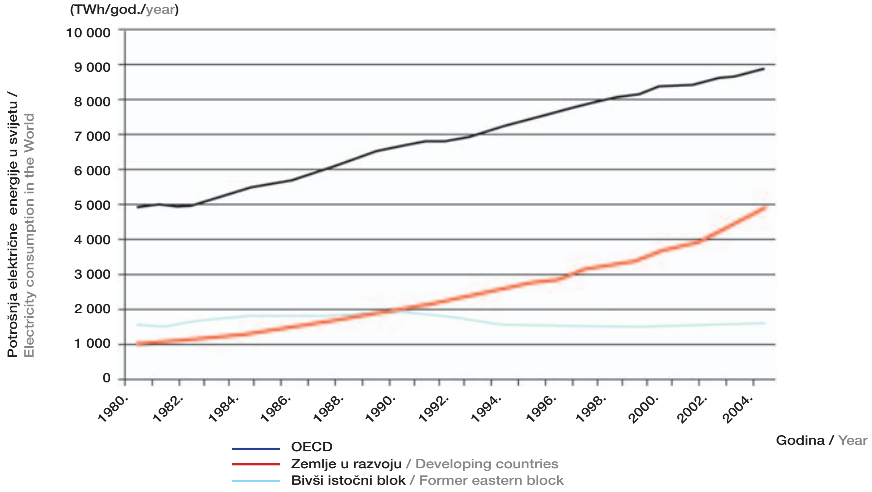
Germany and Sweden decided to reduce the numbers of their nuclear reactors gradually.

Natural gas became the most desirable energy source of the future in many countries. During the period from 1992 to 2003, the percentage of natural gas in the European energy balance rose from 6 % to 18 %, i.e. its consumption for the production of electricity rose over 3,5 times [4].

The greenhouse effect caused by anthropogenic emissions into the atmosphere was identified as a priority in global efforts for protecting the environment and approaching the concept of sustainable development. Renewable energy sources were offered as solutions for the questions of environmental protection and reliable supply. Energy saving and energy efficiency measures were recognized as necessities.

Today, two decades after Chernobyl and five decades after Calder Hall, the situation is changing again. Tremendous growth in the European demand for natural gas has caused supply problems and considerable price increases. The 2006 cutbacks in the delivery of Russian gas helped many European countries recognize the consequences of excessive energy dependence. Due to expected growth in electricity consumption, it is anticipated that Europe will need at least 65 GW of new capacity by 2012. Judging from announcements, this capacity will be met by gas power plants for the most part, which means that the annual gas imports to Europe, presently 230 billion cubic meters, will have to increase to a minimum of 465 billion cubic meters by 2012 [4].

Despite great investments in renewable energy sources (biomass, hydro, wind, solar and geothermal), their share in meeting the total energy requirements is still marginal, only approximately 6 % at the level of the European Union, which is the leader regarding the question of renewable energy sources. The consequences of the greenhouse effect are recognized as real and very current problems. It appears that the Greens are slowly accepting that renewable sources and energy efficiency, although useful, cannot provide a solution on the global level and cannot provide it quickly enough, especially taking into account the tremendous increase in energy demand that characterizes the economies of developing countries, particularly China and India (Figure 3).



Slika 3
Potrošnja električne energije u svijetu [5]
Figure 3
Electricity consumption in the world [5]

Kao posljedica svega navedenog, podrška nuklearnoj energiji u javnosti ponovno počinje rasti. U takvoj situaciji sve više zemalja ponovno razmatra uporabu nuklearne energije ili je već pokrenulo ambiciozne nuklearne programe. Nuklearna industrija u novim okolnostima gradi imidž tehnologije koja u dostatnim količinama, na ekonomičan i siguran način, može ponuditi alternativu fosilnim gorivima, istodobno ne emitirajući stakleničke plinove. Zahvaljujući polustoljetnom iskustvu, nuklearna industrija naučila se nositi s vlastitim nedostatcima te aktivno raditi na njihovom otklanjanju.

3 REZERVE URANA

Za razmatranje mogućnosti da nuklearna industrija preuzme značajniju ulogu u opskrbi električnom energijom potrebno je tehnologiju razmotriti i s aspekta resursa, prije svega zaliha goriva.

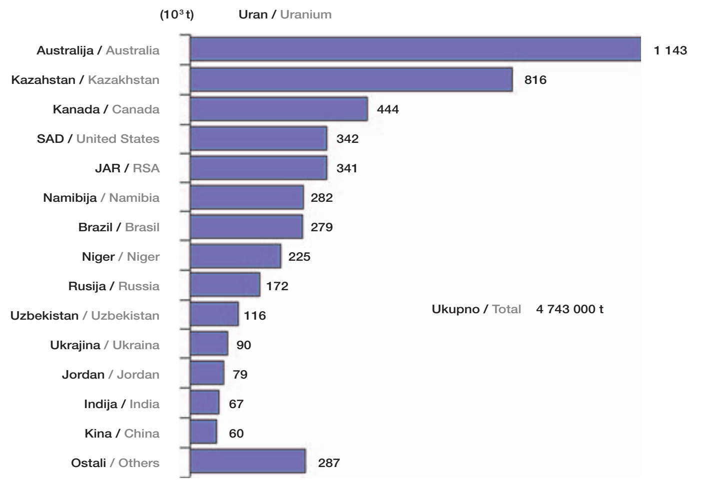
Svjetske zalihe urana procjenjuju se trenutačno na 18 milijuna tona. Pri toj procjeni kao gornja cijena isplativih rezervi uzeta je cijena od 130 USD/kg prirodnog urana.

Due to all the above, public support for nuclear energy is beginning to grow. In such a situation, an increasing number of countries are reconsidering the use of nuclear energy or have already inaugurated ambitious nuclear programs. Under these new circumstances, the nuclear industry is building an image of a technology that can offer an alternative to fossil fuels in sufficient quantities and cost effectively, without emitting greenhouse gases. Owing to half a century of experience, the nuclear industry has learned to deal with its shortcomings and is actively working to eliminate them.

3 URANIUM RESERVES

In discussing the possibilities for the nuclear industry to assume a more significant role in the supply of electrical energy, it is necessary to consider the technology from the aspect of resources, particularly fuel reserves.

World uranium reserves are currently estimated at 18 million tons. With this estimate, the top price for cost-effective reserves is considered to be 130 USD/kg of natural uranium.



Slika 4
Potvrđene svjetske zalihe urana, s cijenom 130 USD/kg urana [6]
Figure 4
Confirmed uranium reserves in the world, at the price of 130 USD/kg of uranium [6]

S današnjom potrošnjom urana od 68 000 tona godišnje jednostavnom aritmetikom možemo zaključiti da su potvrđene zalihe urana dostatne za 70 godina rada pod uvjetom da se potrošnja goriva ne povećava (slika 4).

S obzirom da pri sadašnjim cijenama uranova ruda u cijeni električne energije iz nuklearnih elektrana sudjeluje tek sa 2 % do 3 %, nuklearna industrija prilično je tolerantna na cijenu urana. Upravo iz tog se razloga ne poduzimaju značajnija istraživanja novih rezervi. Ukoliko se graničnu cijenu za definiranje dostupnih rezervi urana podigne sa 130 USD/kg na 260 USD/kg urana (što bi cijenu električne energije podiglo tek za približno 3 %), dostupne rezerve urana se povećavaju za faktor 3. Intenziviranje aktivnosti oko istraživanja novih nalazišta, moglo bi povećati dostupne rezerve i za faktor 10. Korištenje tehnologija s gorivim ciklusima sofisticiranijim od danas prevladavajućeg *once through* povećale bi energiju dostupnu iz sadašnjih rezervi za faktor 1,3 (reprocesiranje jednom) do 60 (kombiniranje višestrukog reprocesiranja i brzih oplodnih reaktora), dok se očekuje da će i samo unaprjeđenje sadašnjih lakovodnih reaktora donijeti racionalizaciju u korištenju urana za oko 25 % u bližoj budućnosti. Uz rezerve prirodnog urana moguće je u nuklearnim reaktorima iskoristiti i nuklearni materijal u postojećim nuklearnim bombama (približno 2 000 tona visokoobogaćenog urana i približno 260 tona plutonija), što bi bilo dovoljno za pokrivanje današnje svjetske potrošnje u idućih nekoliko godina.

U slučaju značajnijeg porasta cijene urana, u perspektivi je moguće razmatrati korištenje tzv. nekonvencionalnih rezervi urana; iz fosfatnih naslaga i iz morske vode. Uran iz tih izvora povećava sadašnje rezerve za faktor 4,5 (fosfatne naslage), odnosno čak približno 850 (morska voda).

At today's rate of consumption (68 000 t/year), with simple arithmetic we can conclude that the confirmed uranium reserves are sufficient for 70 years of operation, provided that fuel consumption does not increase (Figure 4).

Since uranium ore accounts for only 2 % to 3 % of the price of electricity generated by nuclear power plants, the nuclear industry is fairly tolerant of the price of uranium. It is for this reason that significant prospecting for new reserves is not underway. If the uppermost price for defining the available uranium reserves were to rise from 130 USD/kg to 260 USD/kg of uranium (which would raise the price of electricity by approximately 3 %), the available uranium reserves would increase by a factor of 3. The intensification of prospecting for new uranium deposits could increase the available reserves by a factor of 10. The use of technologies with more sophisticated fuel cycles than the once-through fuel cycles prevailing today would increase the available energy from the current reserves by a factor of 1,3 (reprocessing once) to 60 (combined multiple reprocessing and fast reactors), while it is anticipated that merely improving the current light-water reactors would provide approximately 25 % rationalization in the use of uranium in the near future. Besides the natural uranium reserves, in nuclear reactors it is also possible to use nuclear material in existing nuclear bombs (approximately 2 000 tons of highly enriched uranium and nearly 260 tons of plutonium), which would be sufficient for covering current world consumption for several years.

In the event of more significant increases in uranium prices, it is also possible to consider using the so-called unconventional uranium reserves, from phosphate deposits and seawater. Uranium from phosphate deposits would increase the current reserves by a factor of 4,5 and from seawater by a factor of 850.

Današnji način korištenja urana može se smatrati s aspekta tog resursa prilično neracionalan, te je evidentno da postoje razne mogućnosti kojima je energiju sadržanu u uranu moguće iskoristiti na višestruko efikasniji način. Ukoliko će se neke od navedenih opcija implementirati zajedno, dostupna energija iz urana povećat će se i mnogostruko više.

Slijedom navedenog moguće je zaključiti da rezerve urana nisu ograničavajući faktor za razvoj nuklearne industrije. Također nije zanemariva niti činjenica da su svjetske rezerve urana ravnomjernije raspoređene od primjerice nafte i plina, te da se dobar dio tih rezervi nalazi u politički stabilnim zemljama.

Osim goriva, kratkoročni ograničavajući faktori su resursi same industrije. Naime, nakon gotovo dva desetljeća stagnacije i rezanja troškova, nuklearna industrija prilično je smanjila svoje kapacitete, kako u pogledu proizvodnje, tako i u pogledu ljudskih resursa. Najavljivani rast nuklearne industrije, bez sumnje će biti potrebno poduprijeti i stvaranjem novih kapaciteta, kako industrijskih tako i ljudskih.

4 TEHNOLOŠKI RAZVOJ

4.1 Generacija I.

Današnji nuklearni reaktori uglavnom su reaktori takozvane Generacije II. i III. dok su svi reaktori prve generacije umirovljeni [7].

Prvu samoodržavajuću nuklearnu reakciju ostvario je Enrico Fermi sa suradnicima koncem 1942. godine na Sveučilištu u Chicagu. Električna energija iz nuklearnog reaktora po prvi put je proizvedena koncem 1951. godine iz američkog eksperimentalnog reaktora EBR-1, a prva nuklearna elektrana za proizvodnju električne energije započela je s radom 27. lipnja 1954. godine u Obninsku u Rusiji.

Mnogi reaktori Generacije I. bili su, poput reaktora Fermi 1, jedinstveni i nisu se više gradili za razliku od reaktora Generacije II. koji su se gradili u serijama i koji su, iako individualno dizajnirani, koristili iste dizajnerske principe. Neki reaktori prve genercije poput Magnox reaktora, uz manje izmjene, evoluirali su u drugu generaciju nuklearnih reaktora koja se počela graditi od sredine 60-ih godina prošlog stoljeća.

Today's manner of using uranium resources could be called irrational. It is evident that there are various possibilities whereby the energy contained in uranium can be harnessed in a manner that is many times more efficient. Insofar as some of the cited options will be implemented together, the available energy from uranium will increase many more times.

Consequently, it is possible to conclude that the uranium reserves are not a limiting factor for the development of the nuclear power industry. Furthermore, the fact should not be ignored that the world uranium reserves are more evenly distributed than, for example, oil and gas, and that a good portion of these reserves are located in politically stable countries.

In addition to fuels, the resources of the industry itself are short-term limiting factors. After nearly two decades of stagnation and cutting costs, the nuclear industry has reduced its capacities somewhat, in terms of production and human resources. The heralded growth of the nuclear industry will undoubtedly have to be supported by new capacities, both industrial and human.

4 TECHNOLOGICAL DEVELOPMENT

4.1 Generation I

Today's nuclear reactors are generally reactors of the so-called Generations II and III, while all the Generation I reactors have been retired [7].

The first self-sustaining nuclear reaction was achieved by Enrico Fermi and his associates in late 1942 at the University of Chicago. Electricity from a nuclear reactor was first produced in late 1951 from the American experimental reactor EBR-1, and the first nuclear power plant for the production of electricity began operations on June 27, 1954 in Obninsk, Russia.

Many Generation I reactors, such as the Fermi 1 reactor, were unique and are no longer being constructed, unlike Generation II reactors which were built in series and which, although designed individually, share the same designing principles. Some Generation I reactors, such as the Magnox reactor, evolved with minor changes into the Generation II nuclear reactors that were first constructed in the mid 1960s.

4.2 Generacija II.

Nuklearni reaktori druge generacije razvili su se iz svojih prethodnika i gradili su se čitavih 30 godina, do sredine 90-ih godina. Promjene u dizajnu bile su značajne, no ipak ne u cijelosti revolucionarne.

Tipični predstavnici ove najduže epohe u razvoju nuklearne energetike, koja je doživjela svoj procvat početkom 70-ih godina ali i strmoglavi pad narudžbi 80-tih godina, su tlakovodni reaktori (PWR – Pressurised Water Reactor), ključajući reaktori (BWR – Boiling Water Reactor) i napredni plinom hlađeni reaktori (AGR – Advanced Gas Reactors).

Tlakovodni reaktori PWR (Pressurized Water Reactor)

PWR reaktori najrašireniji su tip nuklearnih reaktora u svijetu, njih više od 230 koristi se za proizvodnju električne energije, a nekoliko stotina za pogon nuklearnih podmornica za što su izvorno i bili dizajnirani. Za hlađenje i za moderaciju neutrona koriste vodu pod visokim tlakom, a kao gorivo se obično koristi nekoliko postotaka obogaćen uran-235. Jedina hrvatsko-slovenska nuklearka Krško također je PWR tipa. Slična serija tlakovodnihn reaktora pod nazivom VVER (Vodo-vodnoj energetičeskij reaktor) građena je u bivšem Sovjetskom Savezu i državama Varšavskog bloka. Prvi reaktori ovog tipa razvijeni su prije 1970. godine, dok je noviji dizajn snage 1 000 MW razvijen 1975. godine. Osim što je vrlo sličan PWR-u prošao je i sličan razvojni put, budući da je prvotno razvijan za korištenje u ruskim nuklearnim podmornicama i ratnim brodovima. Kao i u PWR-u, gorivo je malo obogaćeni uranov dioksid UO_2, a moderator i hladioc je obična voda. Danas je u pogonu oko 50 reaktora ovog tipa.

Ključajući reaktori BWR (Boiling Water Reactor)

BWR reaktor vrsta je lakovodnih reaktora koju je razvio General Electric sredinom 50-ih. Ključajuća voda u reaktorskoj jezgri je radni medij koji se koristi za odvođenje topline s nuklearnog goriva i za usporavanje neutrona kako bi se povećala vjerojatnost nuklearne fisije. Zbog svoje robusnosti i relativno jednostavne izvedbe ovi reaktori se nisu razvijali za pogon podmornica, nego isključivo za proizvodnju jeftine električne energije. Za razliku od PWR-a, para proizvedena u reaktoru ide izravno do turbine. Danas je u pogonu više od 80 BWR reaktora.

CANDU (Cada Deuterium Uranium)

CANDU reaktor razvijen je u kasnim 50-im i ranim 60-im godinama u Kanadi. Riječ je o tlakovodnom reaktoru hlađenom teškom vodom. Gorivo je smješteno u tlačne cijevi, okružene teškom vodom

4.2 Generation II

Generation II nuclear reactors developed from their predecessors and were built for a full 30 years, until the mid 1990s. Changes in design were significant but not entirely revolutionary.

Typical representatives of the longest epoch in the development of nuclear energy, that flourished during the 1970s but experienced a steep drop in orders in the 1980s, are the Pressurized Water Reactor – PWR, Boiling Water Reactor – BWR, and Advanced Gas Reactor – AGR.

Pressurized Water Reactor (PWR)

PWR reactors are the most widespread type of nuclear reactors in the world. Over 230 of them are in use for electricity production and several hundred for the powering of nuclear submarines, for which they were originally designed. Water under high pressure is used for cooling and the moderation of neutrons, and uranium-235 enriched by several percentage points is generally used for fuel. The only Croatian-Slovenian nuclear power plant, Krško, is also of the PWR type. A similar series of pressurized water reactors known as Water-Cooled Water-Modulated Energy Reactors (WWER or VVER) was built in the former Soviet Union and the countries of the Warsaw block. The first reactors of this type were developed prior to the year 1970, while the new design with 1 000 MW of power was developed in 1975. Besides being very similar to the PWR, it followed a similar developmental path, since it was initially developed for use in Russian nuclear submarines and warships. As with the PWR, the fuel is slightly enriched uranium dioxide, and the moderator and coolant are ordinary water. Today, approximately 50 reactors of this type are in operation.

Boiling Water Reactor (BWR)

A BWR is a type of light-water reactor developed by General Electric in the mid 1950s. Boiling water in the reactor core is the working medium that is used to conduct heat away from the nuclear fuel and reduce the kinetic energy of neutrons in order to increase the probability of nuclear fission. Due to their bulk and relatively simple construction, these reactors were not developed to power submarines but exclusively for the production of low-cost electricity. Unlike PWRs, the steam produced in the reactor goes directly to the turbine. Today, over 80 BWRs are in operation.

Cada Deuterium Uranium Reactor (CANDU)

The CANDU reactor was developed in the late 1950s and early 1960s in Canada. This is a pressurized reactor cooled with heavy water. The fuel is contained in pressure tubes surrounded by heavy water at low pressure. Due to its superior pod niskim pritiskom. Teška voda zbog boljih moderacijskih svojstava omogućuje korištenje prirodnog urana za gorivo. Danas je u pogonu oko 40 CANDU reaktora, uglavnom u Canadi i Indiji.

Napredni plinom hlađeni reaktor AGR (Advanced Gas Reactor)
AGR reaktori predstavnici su druge generacije britanskih plinom hlađenih reaktora nastalih razvojem Magnox reaktora. AGR koriste grafit kao neutronski moderator i ugljični dioksid za hlađenje goriva. Za razliku od svojih prethodnika, ovi reaktori radi većeg iskorištenja koriste više temperature hladioca. Također kao gorivo koriste obogaćeni uran čime je smanjena potreba za učestalim zamjenama goriva. Danas je u pogonu sedam AGR reaktora. Snage su im 555 MW ili 625 MW. Svi reaktori nalaze se u Velikoj Britaniji.

Kipući reaktor kanalnog tipa RBMK (Reaktor baljšoj mašćnosti Kanaljnij)
RBMK je danas zastarjeli tip grafitnih reaktora hlađenih vodom. Ozloglašeni predstavnik ove generacije nuklearnh reaktora je Černobilj. Kako je VVER reaktor bio tehnološki puno zahtjevniji, bivši Sovjetski Savez se više zalagao za gradnju RBMK reaktora. Osim povoljnih ekonomskih okolnosti, RBMK je mogao koristiti prirodni uran kao gorivo, koje se moglo mijenjati tijekom pogona, dakle bez zaustave i reaktor je proizvodio plutonij za vojne svrhe. Danas je u pogonu još desetak RBMK reaktora i to isključivo u Rusiji.

4.3 Generacija III.

Reaktori ove generacije razvijeni su (i još se razvijaju) poboljšanjem dizajna reaktora iz prethodne generacije. Posebno je poboljšana tehnologija izrade nuklearnog goriva te sigurnosni sustavi.

Prvi reaktor ove generacije u pogonu je od 1996. godine u Japanu. Tipovi reaktora Generacije III. su EPR, AP 1000, ABWR i System 80+.

Europski tlakovodni reaktor EPR (European Pressurized Reactor)
Ovaj reaktor razvija francusko-njemački konzorcij Areva/Siemens. Reaktor može koristiti 5 % obogaćeni uran ili MOX gorivo (miješani oksid urana i plutonija). Dizajn reaktora je napredan u prvom redu zbog povećane sigurnosti (dodano nekoliko pasivnih sigurnosnih sustava), ali i zbog velike izlazne snage (1 600 MW).

U tijeku je gradnja prvog reaktora ove vrste u Finskoj (Olkiluoto 3). Međutim, zbog određenih problema u gradnji, datum puštanja elektrane u pogon pomaknut je za više od 18 mjeseci, tako

moderating properties, heavy water permits the use of natural uranium for fuel. Approximately 40 CANDU reactors are in operation today, mainly in Canada and India.

Advanced Gas Reactor (AGR)
AGRs are representatives of the second generation of British gas-cooled reactors that came about with the development of Maxnox reactors. AGRs use graphite as the neutron moderator and carbon dioxide for cooling the fuel. Unlike their predecessors, these reactors use high temperature coolants for greater efficiency. Furthermore, they use enriched uranium as fuel, thereby reducing the need for frequent fuel replacement. There are seven AGR reactors in operation today, with power ratings of 555 MW or 625 MW. All these reactors are located in Great Britain.

High Power Channel Type Reactor (Reaktor Bolshoy Moshchnosti Kanalniy – RBMK)
The RBMK is now an obsolete type of graphite-moderated water-cooled reactor. The infamous representative of this generation of nuclear reactors was located at Chernobyl. Since the WWER was technologically more demanding, the former Soviet Union invested more in the building of RBMK reactors. Besides economic considerations, the RBMK was able to use natural uranium as fuel, which could be changed during operation, i.e. without shutting down, and the reactor produced plutonium for military purposes. There are still RBMKs in operation today, exclusively in Russia.

4.3 Generation III

Reactors of this generation were developed (and continue to be developed) by improving the design of reactors from the previous generation, particularly the fuel technologies and safety systems.

The first reactor of this generation has been in operation in Japan since 1996. The types of Generation III reactors are the European Pressurized Reactor – EPR, the Advanced Passive 1000 – AP 1000, the Advanced Boiling Water Reactor – ABWR and System 80+.

European Pressurized Reactor (EPR)
This reactor was developed by the French-German consortium of Areva/Siemens. The reactor can use 5% enriched uranium oxide or MOX (mixed uranium plutonium oxide) fuel. The reactor design is advanced, first of all due to increased safety (several passive safety systems have been added), but also due to the high electrical power output (1 600 MW).

The construction of the first reactor of this type is in progress in Finland (Olkiluoto 3). However, due da se prvi kilovatsati očekuju tek početkom 2011. godine. Vrijednost projekta procijenjena je na oko 3 milijarde eura.

AP1000

AP 1000 napredni je reaktor snage oko 1100 MW koji kao i EPR koristi napredne pasivne sigurnosne sustave. AP1000 ima znatno manje ventila, manje cjevovoda, manje kabela, manje pumpi, manje sustava za hlađenje, ventilaciju i zagrijavanje te 45 % manji volumen reaktorske zgrade u odnosu na konvencionalne PWR elektrane. Navedene redukcije vode velikim uštedama u troškovima izgradnje, ali i u trajanju izgradnje (3 godine). Dizajn kojeg razvija Westinghouse službeno je odobren koncem 2005. godine i tijekom 2007. i 2008. godine očekuju se narudžbe za gradnju 10 reaktora [8].

Napredni ključajući reaktor ABWR (Advanced Boiling Water Reactor)

ABWR napredni je dizajn ključajućeg reaktora kojeg razvija General Electric. Glavno poboljšanje u odnosu na postojeće BWR reaktore je smještaj recirkulacijske pumpe i cjevovoda unutar reaktorske tlačne posude, čime je reducirana mogućnost curenja hladioca. U slučaju gubitka hladioca odgovor elektrane je u cijelosti automatiziran budući da čak 72 sata nije potrebna nikakva reakcija operatera. Tri reaktora ove vrste trenutačno su u pogonu u Japanu, a nekoliko ih je u izgradnji (Japan) ili se planira njihova gradnja (Japan, SAD).

Napredni tlakovodni reaktor System 80+

Ovaj reaktorski dizajn razvija ABB Combustion Engineering. Snaga reaktora iznosi 1 300 MW, a jedna od njegovih posebnosti je korištenje plutonijevog goriva, što ga čini zanimljivim u smislu korištenja zaliha nuklearnih materijala iz atomskih bombi. Ovaj tip reaktora razvijen je iz sličnog reaktora PWR reaktora System 80 koji je već u pogonu u nekoliko nuklearnih elektrana u SAD-u i Koreji.

4.4 Generacija III+

Reaktori koji, iako dijelom revolucionarni, ne zadovoljavaju kriterije reaktora Generacije IV. nazivaju se reaktori III+ generacije. Najrazvijeniji prototipovi iz ove generacije su kipući reaktor s pojednostavljenom ekonomijom (ESBWR – Economic Simpified Boiling Water Reactor) i Pebble bed modular reactor (PBMR).

to certain construction problems, the date that this power plant will go on line has been postponed for over 18 months, so that the first kilowatt hours are not expected until early 2011. This project has been estimated to cost approximately 3 billion euros.

Advanced Passive 1000 (AP 1000)

The AP 1000 is an advanced reactor designed to generate approximately 1 100 MW, which like the EPR uses advanced passive safety systems. The AP 1000 has significantly fewer valves, less piping, less cable, fewer pumps, smaller HVAC (heating, ventilation and air conditioning) and 45 % less building volume than a conventional PWR plant. These reductions lead to great savings in construction costs and time (3 years). The design developed by Westinghouse was officially approved in late 2005. Orders are anticipated in 2007 and 2008 for the construction of ten reactors [8].

Advanced Boiling Water Reactor (ABWR)

The ABWR is an advanced boiling water reactor developed by General Electric. The chief improvement in comparison to existing BWRs is the containment of the recirculation pumps and piping inside the reactor pressure vessel, which reduces the possibility of coolant leakage. In the event of a Loss of Coolant Accident (LOCA), plant response has been fully automated and no operator action is required for 72 hours. Three reactors of this type are already in operation in Japan, several are under construction in Japan, or are planned in Japan and the United States.

System 80+ Advanced Pressurized Water Reactor (System 80+ APWR)

This reactor design was developed by ABB Combustion Engineering. The reactor generates 1 300 MW. One of its advantages is the use of plutonium fuel, making it interesting in the sense of being a useful means for the disposal of Weapon Graded Plutonium from dismantled nuclear warheads. This reactor type was developed from a similar System 80 PWR that is already in operation at several nuclear power plants in the United States and Korea.

4.4 Generation III+

Reactors which, although somewhat revolutionary, do not meet the criteria of Generation IV reactors are known as Generation III+ reactors. The most advanced prototypes from this generation are the Economic Simplified Boiling Water Reactor – ESBWR and the Pebble Bed Modular Reactor – PBMR.

ESBWR

Razvoj ESBWR-a se temelji na usavršenom plinom hlađenom reaktoru (ABWR – Advanced Boiling Water Reactor). I ovaj reaktor je dizajnirao General Electric i temelji se na tehnologiji kipućih reaktora.

Reaktor je pasivno siguran, što znači da za njegovu zaustavu u slučaju nekog izvanrednog događaja koji bi u konačnici mogao rezultirati taljenjem jezgre nije potrebna posebna reakcija operatera niti bilo kojeg elektronskog uređaja. Pasivna sigurnost je kod ovog reaktora temeljena na dva sigurnosna sustava: prva komponenta su izolacijski kondenzatori ili izmjenjivači topline koji preuzimaju paru iz reaktora ili zaštitne posude (containmenta), kondenziraju je, prenose toplinu u bazen s vodom te vraćaju vodu ponovno u reaktor, dok se drugi sustav temelji na gravitaciji. Sustav automatski potapa reaktor vodom iz zasebnog bazena iznad reaktora ukoliko dođe do pada razine vode u reaktoru.

Reaktor se hladi prirodnom cirkulacijom hladioca, nema posebnih pumpi za cirkulaciju niti cjevovoda. Jezgra je zbog toga kraća od tradicionalnih BWR reaktora. Ispod reaktora smješten je sustav cjevovoda koji omogućuje hlađenje jezgre tijekom ozbiljne nesreće.

Vjerojatnost istjecanja radioaktivne materije u atmosferu je nekoliko redova veličine niža nego kod konvencionalnih reaktora, a očekivani trošak izgradnje je čak 60 % do 70 % niži nego kod lakovodnih reaktora. Predviđena električna snaga takvog reaktora je 1 550 MW.

PBMR (Pebble Bed Modular Reaktor)

Ovaj reaktor jedan je od naprednih reaktorskih dizajna sa značajno većom iskoristivošću i višom sigurnosnom razinom. Reaktor umjesto vode koristi grafit kao moderator te neki poluinertni plin (helij, dušik ili ugljični dioksid) kao hladioc koji dostiže vrlo visoke temperature i izravno ulazi u plinsku turbinu. Na taj način uspješno se uklanja čitav niz međusustava (npr. parogeneratori) i podiže iskoristivost na približno 50 %. Gorivo se izrađuje u obliku kuglica (pebble = oblutak) s jezgrom od obogaćenog urana i grafitnim plaštem. Reaktor također posjeduje pasivnu sigurnost, a dodatna mu je prednost što se gorivo može mijenjati tijekom pogona. Ovaj reaktorski dizajn inicijalno je razvijao njemački Siemens, a danas na njegovom razvoju radi Westinghouse, Južnoafrička Republika i Kina. Tijekom 2007. godine u Južnoafričkoj Republici planira se početi s gradnjom probnog reaktora koji bi trebao biti gotov do 2011. godine, a 2013. godine trebala bi započeti komercijalna gradnja.

Economic Simplified Boiling Water Reactor (ESBWR)

The development of the ESBWR was based upon improvements made in the gas-cooled Advanced Boiling Water Reactor – ABWR. This reactor was also designed by General Electric and is based upon the technology of boiling water reactors.

The reactor is a passively safe design, which means that in the event of some exceptional occurence that could result in the meltdown of the core, no special reaction is required from the operator or any electronic equipment. The passive safety of this reactor is based upon two safety systems. The first components are isolation condensers, which are heat exchangers that take the steam from the reactor vessel or the containment, condense it, transfer the heat to a water pool and return the water into the reactor. The second system is the Gravity Driven Cooling System (GDCS), which automatically floods the reactor with water from separate pool above the vessel in the event that a low water level is detected in the reactor.

The reactor is cooled by the natural circulation of the coolant. There are no special pumps for circulation or piping. Therefore, the core is shorter than in conventional BWRs. Below the reactor is a piping system that allows for the cooling of the core in the event of a very severe accident.

The probability of the release of radioactive material into the atmosphere is several orders of magnitude lower than for conventional reactors, and the estimated building cost is 60 –70 % lower than for other light-water reactors. The anticipated power rating of such a reactor is 1 550 MW.

Pebble Bed Modular Reactor (PBMR)

This reactor is one of the advanced reactor designs with significantly higher efficiency and safety. Instead of water, it uses graphite as the moderator and an inert or semi-inert gas (helium, nitrogen or carbon dioxide) as the coolant, which reaches very high temperatures and enters the gas turbine directly. In this manner, it eliminates an entire series of intermediary systems, such as the steam generator, and increases transfer efficiency to approximately 50 %. The fuel is manufactured in a pebble shape, with a core of enriched uranium and graphite covering. The reactor also has passive safety. An additional advantage is that the fuel can be changed during operation. This reactor design was initially developed by the German firm of Siemens. Westinghouse, the Republic of South Africa and China are currently working on its further development. During 2007, the beginning of the construction of a demonstration reactor is planned in the Republic of South Africa, which should be completed by 2011, and commercial construction should start in the year 2013.

4.5 Generacija IV.

Reaktori Generacije IV. skup su novih i naprednih tehničkih rješenja koja su trenutačno u razvojnoj fazi. Generalno, za te se reaktore ne očekuje da će biti raspoloživi za komercijalnu proizvodnju prije 2030. godine. Istraživanja o ovoj najnovijoj generaciji nuklearnih reaktora započeo je Međunarodni forum reaktora IV. generacije (Generation IV. International Forum). Primarni ciljevi Foruma su poboljšanje nuklearne sigurnosti, smanjenje mogućnosti proliferacije, smanjenje nuklearnog otpada i smanjenje troškova gradnje i kasnijeg pogona takvih elektrana.

Treba napomenuti da je za ostvarenje takvih ciljeva nužno osmisliti i nove alate za ekonomsku procjenu opravdanosti gradnje reaktora IV. generacije, budući da se njihove karakteristike bitno razlikuju od postojećih reaktora II. i III. generacije.

Početno je razmatran veliki broj raznih reaktorskih dizajna, no njihov broj je ipak reduciran kako bi se bilo moguće fokusirati na najperspektivnije tehnologije. Danas se najviše govori o četiri predstavnika termalnih reaktora i isto toliko brzih oplodnih reaktora.

Visokotemperaturni reaktor VHTR (Very High Temperature Reactor)

VHTR koncept temelji se na helijem hlađenoj jezgri s grafitom kao moderatorom i uranovom gorivnom ciklusu. U reaktoru će se moći dostići temperatura od 1 000 °C. Jezgra može biti u obliku prizme ili kuglica. U oba slučaja uran je uložen u grafit. Za VHTR također se podrazumijeva pasivna sigurnost.

Superkritični vodom hlađeni reaktor SCWR (Supercritical Water Cooled Reactor)

Superkritični vodom hlađeni reaktor je koncept koji koristi superkritičnu vodu kao radni medij. SCWR je u svojoj osnovi lakovodni reaktor koji radi na puno višem tlaku i temperaturi od klasičnih PWR-a i BWR-a. Njegove osnovne prednosti su značajno veći stupanj toplinskog iskorištenja (45 %) u odnosu na 33 % iskoristivosti klasičnih lakovodnih reaktora te znatno tehnološko pojednostavljenje elektrane. Ovaj reaktor predstavlja svojevrsnu kombinaciju PWR i BWR reaktora s glavnim ciljem proizvodnje jeftine električne energije. Na njegovom razvoju rade 32 organizacije iz 13 zemalja.

Reaktor hlađen rastaljenom soli MSR (Molten Salt Reactor)

Kao što mu ime govori, hladioc ovog naprednog reaktorskog dizajna je rastaljena sol. Do sada je predstavljeno više dizajna za ovaj tip reaktora, a napravljeno je i nekoliko prototipova. Ranija rješenja oslanjala su se na nuklearno gorivo

4.5 Generation IV

Generation IV reactors are a group of new and advanced technical solutions that are currently in the developmental stage. It is generally not expected that these reactors will be available for commercial construction before the year 2030. Research on this newest generation of nuclear reactors was begun by the Generation IV International Forum (GIF). The primary goals of the forum are to improve nuclear safety, reduce the possibilities for proliferation, minimize nuclear waste and lower the cost of building and running such plants.

It should be mentioned that for achieving such goals, it is necessary to devise new tools for the economic assessment of the justification for building Generation IV reactors, since their characteristics differ significantly from those of the current Generation II and III reactors.

Initially, a large number of various reactor designs were considered. Their number was eventually reduced in order to focus on the most promising technologies. Today, the most discussed are four representatives of thermal reactors and the same number of fast reactors.

Very High Temperature Reactor (VHTR)

The VHTR concept is based upon a helium-cooled core with graphite as the moderator and a uranium-fueled cycle. It will be possible to reach a temperature of 1 000 °C inside the reactor. The core can be of either a prismatic block or pebble bed form. In both cases, the uranium is imbedded in graphite. The VHTR also implies passive safety.

Supercritical Water Cooled Reactor (SCWR)

The SCWR is a water cooled reactor concept that uses supercritical water as the working fluid. The SCWR is basically a light-water reactor that operates at higher pressures and temperatures than classical PWRs and BWRs. Its basic advantages are a significantly higher thermal efficiency (45 %) in comparison to 33 % efficiency for current light-water reactors and significant technological simplification of the plant. This reactor represents a type of a combination of PWR and BWR reactors, with the main goal of producing low-cost electricity. Thirty-two organizations from 13 countries are working on its development.

Molten Salt Reactor (MSR)

As the name implies, the coolant for this advanced reactor design is molten salt. Until now, many designs have been presented for this type of reactor and several prototypes have been built. Earlier solutions relied upon nuclear fuel dissolved in molten fluoride salt as uranium tetrafluoride. Criticality was reached with the flowing of the otopljeno u rastaljenim solima flora tvoreći uranov tetraflorid. Kritičnost se dosiže dolaskom medija u grafitnu jezgru koja ujedno služi kao moderator. Neki današnji koncepti više se oslanjaju na gorivo disperzirano unutar grafitne matrice s rastaljenom soli čime se osigurava hlađanje pri visokoj temperaturi i niskom tlaku.

Međunarodni inovativan i sigurni reaktor IRIS (International Reactor Innovative and Secure)
IRIS je modularni lakovodni reaktor srednje električne snage (najmanje 335 MW) na čijem razvoju radi Westinghouse zajedno s velikim brojem međunarodnih ustanova među kojima se nalazi i Fakultet elektrotehnike i računarstva iz Zagreba [9]. Dizajn reaktora ima naglašenu otpornost na proliferaciju i udovoljava naprednim sigurnosnim kriterijima koji se postavljaju pred reaktore Generacije IV. Najvažnija poboljšanja su inherentna sigurnost ostvarena na način da su sve glavne komponente smještene unutar zajedničke posude i dodatno, većina sigurnosnih sustava zasniva se na djelovanju prirodnih sila kao što su gravitacija ili prirodna cirkulacija.

Plinom hlađeni brzi reaktor GFR (Gas Cooled Fast Reactor)
Plinom hlađeni brzi reaktor koristi brze neutrone u zatvorenom nuklearnom gorivnom ciklusu za puno efikasnije iskorištenje energetskog potencijala nuklearnog goriva. Stoga je udio cijene goriva u cijeni električne energije kod ovih reaktora značajno reduciran. Reaktor je hlađen helijem, a izlazna mu je temperatura 850 °C.

Brzi reaktori hlađen natrijem SFR (Sodium Cooled Fast Reactor)
SFR predstavlja nadogradnju dva postojeća projekta: LMFBR (Brzi reaktor hlađen tekućim metalima) i IFR (Integralni brzi reaktor).

Cilj projekta je povećati efikasnost korištenja urana kroz oplodnju plutonija te omogućavanje transformacije takozvanih transuranskih izotopa koji još stoljećima svojim ionizirajućim zračenjem opterećuju lokaciju na kojoj se skladište. U reaktoru se nalazi nemoderirana jezgra u kojoj se događa fisija s brzim neutronima. Višak neutrona pruža mogućnost da se transuranski izotopi transformiraju u druge izotope s kraćim vremenima poluraspada ili u nuklearno gorivo.

SFR je hlađen tekućim natrijem, a za gorivo koristi metalnu leguru urana i plutonija. Gorivo je oklopljeno čeličnim košuljicama dok je zazor između košuljice i goriva ispunjen tekućim natrijem.

medium into the graphite core, which also served as the moderator. Some current concepts rely more on fuel dispersed in a graphite matrix, with the molten salt assuring cooling at a high temperature and low pressure.

International Reactor Innovative and Secure (IRIS)
The IRIS is a modulated light-water reactor of medium power rating, a minimum of 335 MW, being developed by Westinghouse together with a large number of international institutions, including the Faculty of Electrical Engineering and Computing in Zagreb [9]. The reactor design has marked proliferation resistance and meets the safety criteria for Generation IV reactors. The most important improvements are passive safety achieved in a manner that the chief components are located inside a common vessel. In addition, the majority of the safety systems are based upon the activity of natural forces such as gravitation or natural circulation.

Gas Cooled Fast Reactor (GFR)
The GFR uses fast neutrons in a closed nuclear fuel cycle to enhance the utilization of the energy potential of nuclear fuel. Therefore, the percentage of the fuel cost in the price of electricity generated by this reactor is significantly reduced. The reactor is cooled with helium and has an outlet temperature of 850 °C.

Sodium Cooled Fast Reactor (SFR)
The SFR is based upon two existing projects, the Liquid Metal Fast Breeder Reactor (LMFBR) and the Integrated Fast Reactor (IFR).

The goal of the project is to increase the efficiency of uranium utilization through breeding plutonium and allow the transformation of the transuranic isotopes that continue to emit ionizing radiation for centuries, creating storage problems. In the reactor is an unmoderated core where fast neutron fission occurs. The excess of neutrons provides for the transuranic isotopes to be transformed into other isotopes with shorter half-lives or into nuclear fuel.

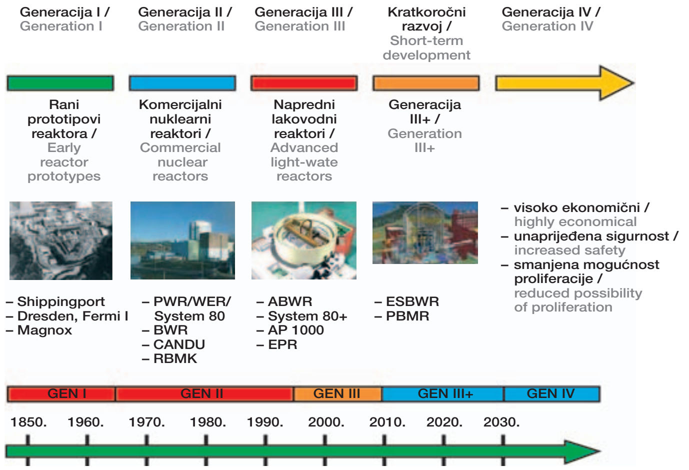
The SFR is cooled by liquid sodium and uses a metallic alloy of uranium and plutonium for fuel. The fuel is contained in steel cladding while the space between the fuel and the cladding is filled with liquid sodium.

Olovom hlađen brzi reaktor LFR (Lead Cooled Fast Reactor)

LFR se odlikuje zatvorenim gorivnim ciklusom s tekućim olovom kao hladiocem. Pogodan je za elektrane različitih snaga, od baterije snage 50 MW do 150 MW s vrlo dugim intervalom izmjene goriva, preko modularnih sistema snage 300 MW do 400 MW pa do velikih kompaktnih blokova od 1 200 MW. Gorivo je bazirano na fertilnom uranu i transuranskim elementima. Reaktor je hlađen prirodnom predajom topline vanjskom hladiocu koji se nalazi na temperaturi od 550 °C. Visoke temperature također omogućuju proizvodnju vodika termokemijskim procesima. Nekoliko ovih reaktora bilo je korišteno za pogon ruskih podmornica, no zbog problema sa skrućivanjem hladioca ovaj reaktorski dizajn više se ne primjenjuje u te svrhe.

Lead Cooled Fast Reactor (LFR)

The LFR is characterized by a closed fuel cycle with liquid lead as the coolant. It is suitable for power plants of various power ratings, from a battery of 50 MW to 150 MW, and features a very long refueling interval, a modular system rated at 300 MW to 400 MW, and large compact blocks of 1 200 MW. The fuel is based on fertile uranium and transuranic elements. The reactor is cooled by natural heat transfer with an outlet coolant at a temperature of 550 °C. The high temperatures also allow the production of hydrogen by thermochemical processes. Several of these reactors were used for powering Russian submarines but due to problems with the hardening of the coolant, this reactor design is no longer used for this purpose.



Slika 5
Razvoj nuklearnih reaktora

Figure 5
The development of nuclear reactors

5 EKONOMSKI ASPEKTI

U poslijeratnom razdoblju nuklearne elektrane razvijale su direktno države, ili su njihov razvoj i izgradnju snažno podržavale.

Elektroprivrede su u tom razdoblju bile u direktnom vlasništvu države ili pod njenom snažnom kontrolom, a tržište električne energije bilo je monopolističko. Planiranje razvoja elektroenergetskog sustava bilo je centralizirano i dugoročno. Projekti izgradnje novih nuklearnih elektrana bili su izloženi niskom regulatornom riziku, imali su pristup relativno jeftinom kapitalu, a rizik na povrat investicije bio je nizak, s obzirom da su svi troškovi prenošeni na kupce električne energije. Snažan gospodarski uzlet nakon rata za sobom je nosio i značajno povećanje konzuma energije. Te su okolnosti u 1970-tim i 1980-tim godinama pogodovale značajnom rastu nuklearne industrije.

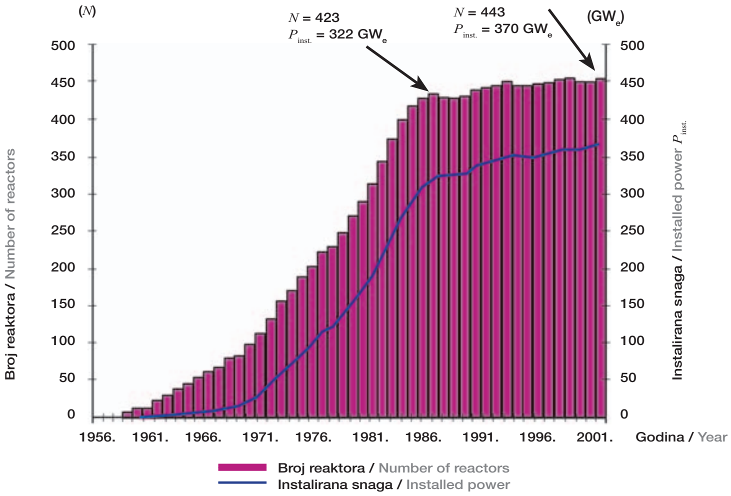
5 ECONOMIC ASPECTS

After the Second World War, nuclear power plants were developed directly by governments or their development and construction received strong government support.

During this period, electrical supply companies were under direct state ownership or under their powerful control, and the electricity market was monopolistic. The planning of the development of the electricity system was centralized and long range. The projects for the construction of new nuclear power plants had low regulatory risk, access to relatively inexpensive capital, and low risk for investment return, since all the costs were transferred to the electricity consumer. The tremendous economic growth after the war led to a significant increase in energy consumption. During the 1970s and 1980s, these circumstances favored the significant growth of the nuclear industry.

Porast instalirane snage reaktora u periodu od 1965. do 1975. godine rastao je po prosječnoj godišnjoj stopi od preko 30 %, dok je u periodu 1965. do 1985. godine prosječni godišnji rast industrije bio preko 20 % (slika 6).

The growth in the installed power of reactors during the period from 1965 to 1975 increased at an average annual rate of over 30 %, while during the period from 1965 to 1985 the average industrial growth rate was over 20 % (Figure 6).



Slika 6
Instalirani nuklearni kapaciteti krajem 2006. u svijetu [1].

Figure 6
Installed nuclear capacities in the world at the end of 2006 [1]

Iako je u sedamdesetim i prvoj polovini osamdesetih nuklearna industrija bilježila snažnu ekspanziju, mnogi pokazatelji su u mnogome ukazivali na dječje bolesti. Izgradnju su često obilježavala prekoračenja budžeta i rokova, dok je pogon reaktora bio obilježen velikim brojem ispada i relativno niskom raspoloživosti postrojenja. Uz to je u SAD-u došlo do nesreće na elektrani Otok tri milje (TMI). Iako nije ispuštena veća količina radioaktivnosti u okoliš i niti jedan pojedinac nije nastradao, taj je događaj značajno utjecao na percepciju javnosti o nesigurnosti nuklearnih elektrana. S aspekta nuklearne industrije, taj je događaj ukazao na nekoliko činjenica: zaštine mjere nuklearnih reaktora od ispuštanja radioaktivnosti u okoliš te zaštite pojedinaca dobro su odradile svoju namjenu, te su posljedice po ljude i okoliš praktički bile zanemarive. S druge strane, ekonomske štete od nuklearne nesreće, prvenstveno za vlasnika postrojenja su značajno veće od očekivanja; čišćenje postrojenja je skup i dugotrajan proces, a izgubljena proizvodnja golema. To je natjeralo nuklearnu industriju da uloži dodatne napore u poboljšanje sigurnosti nuklearnih elektrana, kako radi percepcije javnosti, tako i zbog ekonomskih razloga.

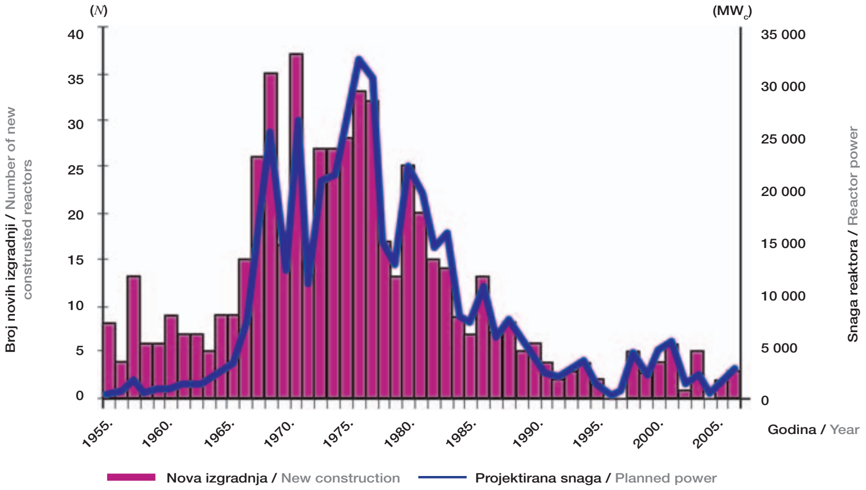
Već spomenuta katastrofa u Černobilju 1986. godine, iako na sasvim drugom konceptu reaktora od zapadnih, snažno je uzdrmala nuklearnu industriju. Naftne krize iz sedamdesetih i ranih osamdesetih bile su prošlost i cijena nafte ponovno je bila niska.

Although the nuclear industry recorded powerful expansion during the 1970s and first half of the 1980s, it was not without growing pains. There were frequent budget overruns and unmet construction deadlines. Reactor plants were characterized by frequent outages and relatively low plant availability. Moreover, the Three Mile Island accident occurred in the United States. Although large quantities of radioactivity were not released into the environment and not a single person was injured, this event had a powerful negative impact on public perception regarding the safety of nuclear power plants. From the aspect of the nuclear industry, this event demonstrated several facts: the safety measures at nuclear reactors to prevent the discharge of radioactivity into the environment and protect persons had performed their intended purpose well, and the consequences to persons and the environment were practically negligible. On the other side, the economic repercussions from the nuclear accident, first of all to the owner of the plant, were far greater than expected. The cleaning of the plant is an expensive and long process, and production losses are enormous. This forced the nuclear industry to invest additional efforts into improving the safety of nuclear power plants, due to both public perceptions and economic considerations.

The previously mentioned catastrophe in Chernobyl in 1986, although based on a reactor with a completely different concept than those in the West, powerfully shook the nuclear industry. The oil crisis from the 1970s and early 1980s had passed and the price of oil was once again low.

Kao posljedica svega navedenog, krajem 1980-tih godina značajno pada broj novih narudžbi, a nuklearna industrija bilježi stagnaciju (slika 7). Nakon dva desetljeća intenzivog rasta, udio nuklearne energije počeo se stabilizirati na 16 % do 17 % u globalnoj proizvodnji električne energije.

As a consequence of everything that has been cited, in the late 1980s there was a significant decrease in the number of new orders, and the nuclear industry recorded stagnation (Figure 7). After two decades of intense growth, the share of nuclear energy began to stabilize at 16 – 17 % of global electricity production.



Slika 7
Broj pokrenutih novih izgradnji, brojčano i po snazi reaktora [1].
Figure 7
Newly constructed reactors, according to numbers and projected power ratings [1]

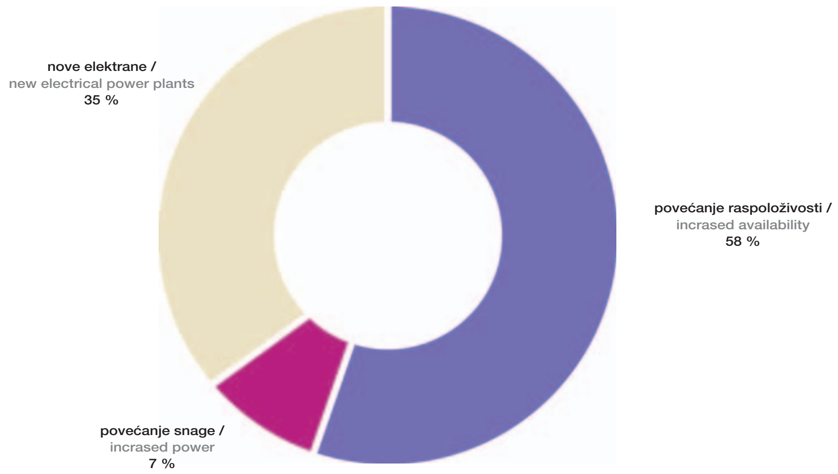
Nuklearna industrija okrenula se poboljšanjima performansi postojećih reaktora, prije svega povećanju njihove raspoloživosti i pouzdanosti, te povećanju snage postojećih reaktora. Uz to su ulagani značajni napori u snižavanje troškova pogona.

Porast proizvodnje električne energije u nuklearnim elektranama od devedesetih na dalje, tek je u manjoj mjeri posljedica puštanja u pogon novih reaktora, a većim dijelom je posljedica povećanja raspoloživosti postojećih elektrana (slike 8 i 9). U periodu od 1990. do 2004. godine godišnja proizvodnja električne energije iz nuklearnih elektrana porasla je s 1 901 TWh na 2 619 TWh, tj 37 %, dok je izgrađenih novih kapaciteta bilo tek 6,7 % više.

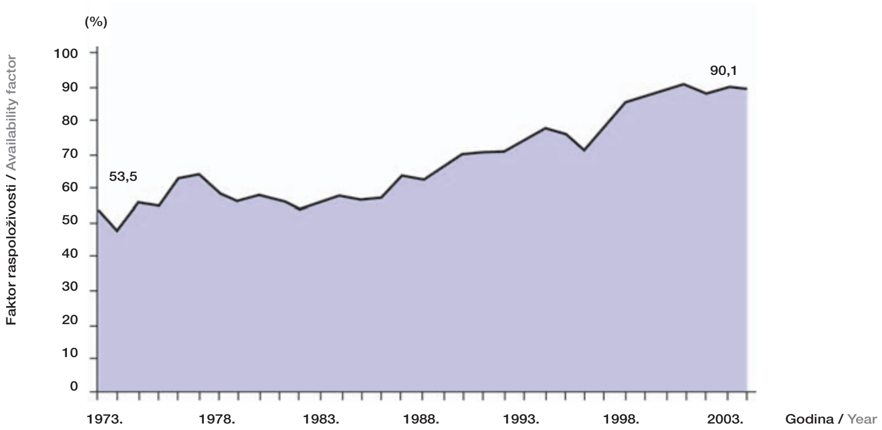
The nuclear industry turned to improving the performance of existing reactors, first of all to increasing their availability, reliability and power ratings. Significant efforts were also invested in reducing plant costs.

The increase in the production of electricity in nuclear power plants since the 1990s is only to a lesser extent a consequence of placing new plants into operation, and to a greater extent a consequence of increasing the availability of the existing plants (Figures 8 and 9). During the period from 1990 to 2004, the annual production of electricity from nuclear power plants rose from 1 901 TWh to 2 619 TWh, i.e. 37 %, while there were only 6,7 % more new plants constructed.

Slika 8
Uzrok povećanja proizvodnje nuklearnih elektrana u svijetu od 1990. – 2004. [10]
Figure 8
Factors increasing production from nuclear power plants in the world, 1990 – 2004 [10]

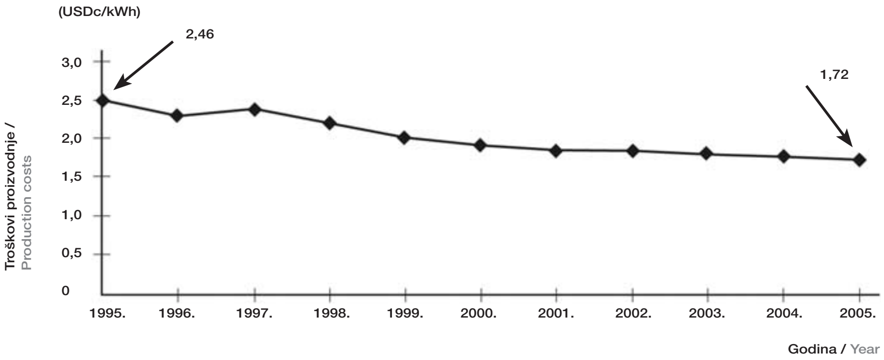


Slika 9
Faktor raspoloživosti američkih nuklearnih elektrana [6]
Figure 9
The availability factor of American nuclear power plants [6]



Povećanje raspoloživosti pogona omogućilo je značajno veću proizvodnju iz postojećih elektrana. U kombinaciji sa sustavnim snižavanjem troškova pogona i održavanja, nuklearna industrija je unatoč snažnom porastu cijene urana uspjela značajno sniziti troškove proizvodnje kWh električne energije (slika 10).

Increased plant availability permitted significantly greater production from existing power plants. Together with the systematic reduction in plant costs and maintenance, despite the considerable increase in the price of uranium, the nuclear industry succeeded in significantly lowering the production costs of a kWh of electrical energy (Figure 10).



Slika 10
Troškovi proizvodnje nuklearnog kWh u SAD-u [6]

Figure 10
Production costs for a nuclear kWh in the United States [6]

U devedesetima je energetika počela prolaziti kroz neke fundamentalne promjene. Glavni razlozi su: liberalizacija tržišta, privatizacija elektroprivrednih kompanija, problemi sigurnosti opskrbe te efekt staklenika.

Konsolidacija same nuklearne industrije, kao i navedeni eksterni faktori ponovo su učinili nuklearnu industriju atraktivnom investitorima i korisnicima električne energije.

Ekonomske prednosti nuklearne industrije nedvojbene su kod već izgrađenih reaktora. Već izgrađeni reaktori, naročito oni već otplaćeni, tj. oni koji imaju samo operativne troškove su prilično profitabilni i danas proizvode gotovo najjeftiniju struju na tržištu. Kod novih reaktora je sitacija nešto drugačija, a s obzirom na to da u Zapadnoj Europi već gotovo 20 godina nije započela gradnja niti jednog novog reaktora, nalaze studija teško je verificirati. Smjer u kojem ide razvoj nuklearne industrije ide k sve većim jedinicama kako bi se u što većoj mjeri ostvarile koristi od ekonomije veličine. Taj smjer međutim nosi i mnoge nedostatke: velik investicijski rizik, veliki i komplicirani projekti, relativno mali broj novoizgrađenih reaktora te mala mogućnost za standardizaciju, spora krivulja učenja i dugo vrijeme izgradnje. U tablici 1 predstavljeni su rezultati nekolicine recentnijih studija o troškovima proizvodnje električne energije iz nuklearnih elektrana. Rezultati su prilično različiti zbog različitosti ulaznih pretpostavki, što također dobro oslikava rizike koje nosi nuklearni projekt.

In the 1990s, energetics began to experience several fundamental changes. The main reasons were the liberalization of the markets, the privatization of electric companies, problems in the dependability of the supply and the greenhouse effect.

The consolidation of the nuclear industry itself, as well as the previously mentioned external factors, once again made the nuclear industry attractive to investors and electricity consumers.

The economic advantages of the nuclear industry are undoubtedly greater in the case of reactors that have already been built. Such reactors, especially those which have been paid for, i.e. those which have only operative costs, are fairly profitable and produce what is nearly the least expensive electricity on the market today. With new reactors, the situation is somewhat different, taking into account that for the past 20 years construction has not begun on single new reactor in Europe, so that study findings are difficult to verify. The direction in which the development of the nuclear industry is going is toward increasingly larger units, in order to achieve the maximum benefits from the economy of size. However, this direction also includes many shortcomings: high investment risk, large and complicated projects, the relatively small number of newly built reactors, little possibility for standardization, the slow learning curve and long construction time. In Table 1, the results of several recent studies on the costs of producing energy from nuclear power plants are presented. The results are fairly diverse due to the diversity of the input parameters, and also illustrate the risks of nuclear projects.

Tablica 1 – Usporedba procijenjenih troškova nuklearne električne energije [11]
Table 1 – Comparison of the estimated costs of nuclear electricity [11]

Izdavač / Publisher	Naziv Studije / Study Title	Izdana / Published	Trošak proizvodnje / Production Costs (EUR/MWh)
Lappeenranta University of Technology	Finnish 5th Reactor Economic Analysis	2002.	24
UK Performance and Innovation Unit	The Economics of Nuclear Power	2002.	34 – 56
Massachusetts Institute of Technology	The Future of Nuclear Power	2003.	55 – 65
The Royal Academy of Engineers	The Costs of Generating Electricity	2004.	34
University of Chicago	The Economic Future of Nuclear Power	2004.	43 – 58
Canadian Energy Research Institute	Levelised Unit Electricity Cost Comparison of Alternative Technologies for Base load Generation in Ontario	2004.	49
IEA/NEA	Projected Costs of Generating Electricity: 2005 Update	2005.	18 – 56

Konkurentnost nuklearnih elektrana u odnosu na elektrane na fosilna goriva različita je u pojedinim zemljama, te načelne ocjene nisu jednoznačne. U komparaciji alternativa potrebno je također imati na umu stalan i u posljednje vrijeme izražen trend porasta cijena fosilnih goriva, te tendenciju da se kWh iz elektrana na fosilna goriva optereti i naknadom za ispuštanje stakleničkih plinova. Iako su dugoročna predviđanja nezahvalna, s današnjim trendovima nuklearne elektrane su dugoročno vrlo atraktivan izbor.

Istodobno treba imati na umu da će neke od promjena koje se odvijaju u energetici postaviti i nove izazove pred nuklearnu industriju. Privatizacija i liberalizacija će prije svega pred investitore postaviti značajno veće rizike na povrat investicije. Uz napore koje ulaže industrija da nuklearne elektrane učini što atraktivnijom opcijom ulagačima, bez sumnje će i države morati prilagoditi pristup, prije svega u smislu licenciranja i regulatorne nesigurnosti.

The competitiveness of nuclear power plants in comparison to fossil fuel power plants is different in individual countries, and the principle assessments are not unambiguous. In comparison to alternatives, it is also necessary to bear in mind the recent marked trend of rising fossil fuel prices and the tendency for an extra charge to be levied on kWh from fossil fuel power plants for greenhouse gas emissions. Although long-term projections are unrewarding, with the current trends nuclear power plants are a very attractive long-term choice.

At the same time, it is necessary to bear in mind that some of the changes that are occurring in energetics will also pose new challenges to the nuclear industry. Privatization and liberalization will pose a significantly greater risk to investors in terms of returns on their investments. Besides the efforts by industry to make nuclear power plants an attractive option to investors, governments will undoubtedly have to adapt their approach, particularly regarding the questions of licensing and regulatory uncertainties.

6 OTPAD

Tipična nuklearna elektrana s tlakovodnim reaktorom električne snage 1 000 MW koja u jednoj godini proizvede oko 7,5 TWh električne energije, pri tome proizvede 200 – 350 m^3 nisko i srednjeradioaktivnog otpada, oko 25 tona, odnosno oko 20 m^3 visokoradioaktivnog otpada te oko 25 tona istrošenog goriva. Nisko i srednjeradioaktivni otpad čine zaštitna odjeća radnika, alati, krpe, istrošeni filteri, istrošene ionske smole i slično.

Doktrina zbrinjavanja otpada u nuklearnoj industriji je koncentrirati i izolirati, za razliku od doktrine, koja se primjenjuje u npr. termoelektranama na fosilna goriva raspršì i razrijedi.

Odlagališta radioaktivnog otpada se dizajniraju tako da se raznim inžinjerskim strukturama sprječava kontakt radioaktivnih materijala i okoline za vrijeme dok mogu predstavljati opasnost za okolinu.

Danas su u svijetu poznate i u primjeni mnoge metode obrade i zbrinjavanja i odlaganja nisko i srednjeradioaktivnog otpada, dok su metode za trajno i konačno zbrinjavanje visokoradioaktivnog otpada još uvijek u fazi ispitivanja (Yucca Mountain u SAD i ONKALO u Finskoj).

6.1 Zbrinjavanje nisko i srednjeradioaktivnog otpada

Nisko i srednjeradioaktivni otpad uobičajeno se zbrinjavaju u plitkim (površinskim ili pripovršinskim) ili dubokim odlagalištima. U tu svrhu se konstruiraju višestruke inženjerske barijere koje će osigurati višegodišnju izoliranost skladišta radi onemogućavanja kontakta radioaktivnih nuklida sa životnom sredinom, posebice podzemnim vodama.

Uobičajena tehnologija podrazumijeva ulaganje bačava s otpadom u armiranobetonske posude te ispunjavanje međuprostora betonom ili sličnim materijalom. Tako dobiveni blokovi odlažu se u betonirane tunele obložene nepropusnom glinom.

Kako je sprječavanje kontakta radionuklida s podzemnim i površinskim vodama jedan od najvažnijih zadataka, često se i čitavo skladište oblaže slojem vodonepropusnog materijala te se također ugrađuje i sustav kontrole drenaže vode koja bi eventualno prodrla u odlagalište.

Duboko odlaganje temelji se na identičnim osnovnim principima izolacije od okoline kao i plitko. Takva se odlagališta grade u stabilnim geološkim formacijama na dubinama od više desetaka do više stotina metara ispod površine

6 WASTES

A typical nuclear power plant with a pressurized water reactor and a power rating of 1 000 MW that produces approximately 7.5 TWh of electricity annually also produces 200 – 350 m^3 of low-level and medium-level radioactive wastes, approximately 25 tons or 20 m^3 of high-level radioactive wastes, and approximately 25 tons of spent fuel. Low-level and medium-level radioactive waste consists of protective workers' clothing, tools, rags, spent filters, spent ionic resins etc.

The doctrine for the disposal of wastes in the nuclear industry is concentrate and isolate, unlike the doctrine applied, for example, to fossil fuel thermoelectric power plants, which is disperse and dilute.

Repositories for radioactive wastes are designed with various engineering structures in order to prevent contact between radioactive materials and the environment for the period of time that they can pose a hazard to the environment.

Today, many methods are known and applied in the world for processing and disposing of low-level and medium-level radioactive wastes, while methods for the permanent and final disposal of high-level radioactive wastes are still in the investigative phase (Yucca Mountain in the United States and ONKALO in Finland).

6.1 The Disposal of Low-Level and Medium-Level Radioactive Wastes

Low-level and medium-level radioactive wastes are usually disposed of in shallow (surface or near surface) or deep repositories. For this purpose, multiple engineering barriers are constructed that will assure many years of isolation, in order to prevent contact between radioactive nuclides and the environment, particularly with underground waters.

The customary technology means the storage of barrels containing wastes in reinforced concrete vessels and filling the spaces with concrete or a similar material. Such blocks are then stored in concrete repository tunnels that are covered with impermeable clay.

Since the prevention of contact between radionuclides and underground and surfaces waters is one of the most important tasks, the entire repository is often coated with a layer of water-impermeable material and a system of controlled drainage water is installed that could eventually penetrate into the repository.

Deep repositories are constructed according the identical basic principles of isolation from the environment as are shallow repositories. Such repositories are built in stable geological formations at depths of zemlje. Stabilne geološke formacije i duboko zakapanje pružaju dodatnu sigurnost da će radionuklidi ostati izolirani od okoline dok god za nju predstavljaju opasnost.

Nisko i srednjeradioaktivni otpad sadrži radioizotope koji gube radiotoksičnost u vremenskom periodu od nekoliko godina pa do najviše nekoliko stotina godina. Osiguravanje izolacije u tom relativno kratkom vremenu ne predstavlja problem, te se smatra da današnja odlagališta tog otpada uspješno rješavaju taj problem. Mnoge države imaju odlagališta za srednje i nisko radioaktivni otpad koja normalno rade već dulji niz godina.

6.2 Zbrinjavanje istrošenog goriva

Za razliku od nisko i srednjeradioaktivnog otpada, istrošeno gorivo zadržava svoju radiotoksičnost i više od 100 000 godina, te trajno zbrinjavanje tog otpada predstavlja značajno veći izazov. Istrošeno gorivo po izlasku iz reaktora sadrži samo oko 3 % fisijskih produkata, tj. pravog otpada. Reprocesiranjem se fisijski produkti izdvajaju i nakon toga ustakljuju te tako odlažu kao visokokoncentrirani visokoradioaktivni otpad. Alternativa tome je direktno odlaganje, tj. gorivi elementi se odlažu u posebno konstruirane spremnike i takvi odlažu u duboka geološka odlagališta.

Prednost reprocesiranja leži u tom što se značajno smanjuje volumen otpada za odlaganje, te u tome što se najveći dio istrošenog goriva može ponovno koristiti u gorivom ciklusu nuklearnih reaktora. Nedostatci su u danas visokoj cijeni procesa te u opasnosti od proliferacije plutonija izdvojenog reprocesiranjem. Tablica 2 prikazuje prihvaćene strategije u raznim državama u svijetu.

tens to hundreds of meters below the surface of the earth. Stable geological formations and deep burial provide additional assurance that the radionuclides will remain isolated from the environment as long as they represent a hazard.

Low-level and medium-level wastes contain radioisotopes that lose their radiotoxicity within a period of from several years to a maximum of several hundred years. The problem of insuring their isolation for this relatively short time is considered to have been successfully solved by today’s repositories. Many countries have repositories for low-level and medium-level radioactive wastes that have operated normally for many years.

6.2 The Disposal of Spent Fuel

Unlike low-level and medium-level radioactive wastes, spent fuel retains its radiotoxicity for over 100 000 years, and the permanent disposal of this waste represents a considerably greater challenge. Upon leaving the reactor, spent fuel contains only 3 % fission products, i.e. genuine waste. Through reprocessing, the fission products are separated and afterward placed in glass and disposed of as highly concentrated high-level radioactive waste. An alternative to this is direct disposal, i.e. the fuel elements are placed in specially constructed vessels and then placed in deep geological repositories.

The advantages of reprocessing lie in the significant reduction in the volume of waste for disposal and that most of the spent fuel can be reused in the fuel cycle of nuclear reactors. The shortcomings are in the high cost of the process and the danger of the proliferation of plutonium separated by reprocessing. Table 2 shows the accepted strategies in the regimes of various countries throughout the world.

Tablica 2 – Pregled strategija postupanja s istrošenim gorivom [6]
Table 2 – Strategies for dealing with spent nuclear fuel [6]

Država / Country	Direktno odlaganje / Direct disposal	Reprocesiranje / Reprocessing
Belgija / Belgium	✓	✓
Kanada / Canada		
Kina / China	✓	✓
Finska / Finland		
Francuska / France		✓
Njemačka / Germany		✓
Indija / India		✓
Japan / Japan		✓
Rusija / Russia	✓	✓
Južna Koreja / South Korea	✓	
Španjolska / Spain	✓	
Švedska / Sweden		
Švicarska / Switzerland		✓
Velika Britanija / Great Britain	✓	✓
SAD / United States		

S obzirom da još uvijek niti jedno trajno odlagalište visokoradioaktivnog otpada nije u pogonu, visokoradioaktivni otpad se trenutno skladišti u privremenim odlagalištima. Primjenjuju se tehnologije mokrog i suhog skaldištenja. Mokro skaldištenje se odvija u bazenima za istrošeno gorivo u sklopu nuklearnih elektrana ili u za tu svrhu posebno izgrađenim centralnim objektima, dok je suho odlaganje obavlja u dizajniranim suhim spremnicima casks.

Pri skladištenju visokoradioaktivnog otpada, osim izolacije radionuklida od okoline potrebno je osigurati stalno i efikasno hlađenje istrošenog goriva koje emitira toplinu još dosta godina po vađenju iz reaktora.

Troškove zbrinjavanja otpada nije moguće odrediti s potpunom sigurnošću s obzirom da još ne postoje konkretna iskustva s trajnim odlaganjem visokoradioaktivnog otpada, ali se u većini analiza i studija procjenjuje da troškovi zbrinjavanja otpada, uključujući razgradnju nuklearne elektrane, sudjeluju u ukupnoj cijeni električne energije iz nuklearnih elektrana s oko 10 %.

U prijašnjim desetljećima je pitanje trajnog rješavanja pitanja visokoradioativnog otpada bilo zanemarivano, te odgađano za budućnost. Danas sve više država uviđa da je to pitanje nužno riješiti što prije kako bi se omogućilo i opravdalo daljnje korištenje nuklearne energije.

Since not a single permanent repository for high-level radioactive waste is in operation, high-level radioactive waste is currently stored in temporary repositories. The technologies of wet and dry storage are used. Wet storage means placing the spent fuel in pools within the grounds of the nuclear power plants or specially constructed central objects for this purpose, while dry storage involves placing the spent fuel in specially designed dry storage casks.

In the storage of high-level radioactive waste, in addition to the isolation of the radionuclides from the environment, it is necessary to provide constant and efficient cooling of the spent fuel, which emits heat for many years after being removed from the reactor.

It is not possible to determine the costs for the disposal of wastes with complete certainty because there is no concrete experience with the permanent storage of high-level radioactive wastes, but in the majority of analyses and studies it is estimated that the costs of waste disposal, including the decommissioning of nuclear power plants, comprise approximately 10 % of the total price of electricity from nuclear power plants.

In past decades, the question of the permanent solution to the problem of high-level radioactive waste received little attention and was postponed for the future. Today, an increasing number of countries realize that it is necessary to resolve this question as soon as possible in order to facilitate and justify the continued use of nuclear energy.

7 SIGURNOST

Primarna pažnja javnosti i investitora usmjerena je na rizik od udesa na nuklearnom reaktoru s oslobađanjem radioaktivnosti u okoliš. Zbog specifičnog rizika sigurnost je od početaka bila odlučujući kriterij kod izgradnje nuklearnih elektrana, rezultirajući u konzervativnim tehničkim i termodinamičkim parametrima goriva i rashladnog sustava. Zbog niske cijene urana učinak na ekonomiju bio je malen, ali je konzervativnost u projektiranju imala nepovoljan učinak na investicijske troškove.

Opsežna probabilistička studija nuklearne sigurnosti WASH-1400 [12] objavljena 1974. godine omogućila je uočavanje komponenata koje u većoj mjeri doprinose riziku i time racionalniju primjenu kozervativnog projektiranja. Veličina koja se koristi za kvantitativno izražavanje sigurnosti reaktora je vjerojatnost talenja reaktorske jezgre VTJ ili CMP (Core Melting Probability). Takav događaj počinje s nekim inicijalnim kvarom, razvija se pretpostavkom slijeda drugih kvarova koji mogu konačno dovesti do izostanka hlađenja jezgre. Semi-empiričkom probabilističkom metodom računaju se doprinosi svih inicirajućih događaja da bi njihov zbroj dao ukupnu vjerojatnost taljenja jezgre reaktora. Analizom učestalosti inicirajućih kvarova za razdoblje od 1969. do 1974. godine došlo se do godišnje vjerojatnosti taljenja jezgre od 10^{-4} do 10^{-3}, bliže višoj vrijednosti [13]. Jedno topljenje na reaktoru elektrane Otok Tri Milje (bez Černobilja kao reaktora irelevantnog za zapadnu reaktorsku tehnologiju) u 10 000 reaktor-godina pogona do 2005. godine potvrđuje procjenu.

Brojna poboljšanja sigurnosti na lakovodnim reaktorima PWR i BWR tipa u pogonu, primijenjena nakon udesa na elektrani Otok Tri Milje smanjila su vjerojatnosti taljenja jezgre za 6 odnosno 8 puta [14]. Analiza inicirajućih događaja u razdoblju od 1980. do 1982. godine dala je vjerojatnost taljenja jezgre oko 1,5 x 10^{-4} i zatim 10^{-4} za sredinu 80-tih godina. No, već projekti novih reaktora izvedeni u 80-tim godinama mogli su ugraditi rezultate sigurnosnih studija i analiza i postići veliko smanjenje vjerojatnosti taljenja jezgre.

Tako je izračunata vjerojatnost taljenja jezrge reaktora Sizewell B, koji je u pogonu od 1995. godine, smanjena na 1,1 x 10^{-6}. Slične, gotovo sto puta manje vrijednosti nego u 80-tim godinama imaju i drugi novi projekti kao američki AP600 ili finski PWR reaktor Olkiluoto 3 u gradnji. Zaštitna zgrada oko reaktora (bez koje je bio Černobiljski reaktor) smanjuje vjerojatnost širenja radioaktivnosti u okoliš na oko 3 x 10^{-9}, pa i manje.

7 SAFETY

The primary attention of the public and investors is focused on the risk from an accident at a nuclear reactor with the release of radioactivity into the environment. Due to this specific risk, safety was the deciding criterion from the beginning in the construction of nuclear power plants, resulting in a conservative technique and thermodynamic parameters for fuel and the cooling system. Due to the low price of uranium, the impact on the economy was slight. Nevertheless, conservatism in designing had an unfavorable impact on investment costs.

An exhaustive probability study on nuclear safety, WASH-1400 [12], published in the year 1974, made it possible to identify the components that largely contribute to the risk and apply conservative design practices rationally. The value that is used for the quantitative expression of the safety of a reactor is the Core Melting Probability (CMP). Such an event begins with an initial equipment problem and develops with the assumption of a sequence of other problems which can ultimately lead to loss of core cooling. Using the semi-empirical probabilistic method, the contributions of all the initiating events are computed, the sum of which yields the total value of the Core Melting Probability of a reactor. Thorough analysis of the frequency of initiated equipment problems for the period from 1969 to 1974 yielded annual Core Melting Probabilities of from 10^{-4} to 10^{-3}, closer to the higher value [13]. One core melting in a reactor at Three Mile Island (not counting Chernobyl because this reactor is irrelevant for Western reactor technology) out of 10 000 cumulative reactor years up to the year 2005 confirms this estimate.

Numerous security improvements on light-water reactors of the PWR and BWR types in operation, which were applied after the accident at Three Mile Island, have reduced Core Melting Probability by 6 or 8 times [14]. Analysis of the initiating events during the period from 1980 to 1982 yielded a CMP of approximately 1,5 x 10^{-4} and then 10^{-4} for the mid 1980s. However, the projects for new reactors constructed during the 1980s were already able to incorporate the results of the safety studies and analyses, and achieved even greater reduction of the CMP.

Thus, the calculated Core Melting Probability of the Sizewell B reactor, which has been in operation since 1995, was reduced to 1,1 x 10^{-6}. Similarly, other new projects such as the American AP 600 and the Finnish PWR Olkiluoto 3 under construction have nearly one hundred times lower probabilities than those built during the 1980s. A protective building around a reactor (which the

S tisuću reaktora u pogonu jedno talenje jezgre moglo bi se očekivati u tisuću godina, a kada bi se dogodilo, vjerojatnost širenja radioaktivnosti u okoliš bila bi manja od jedan posto zahvaljujući zaštitnoj zgradi. To je izuzetan stupanj sigurnosti prihvatljiv i za najgušće naseljena područja.

Rad na unaprjeđenju nuklearne sigurnosti svejedno se i dalje nastavlja u okvirima medjunarodnih projekata INPRO, reaktora Generacije IV. i drugim, ali prioritet nije daljnje smanjenje vjerojatnosti taljenja jezgre. Smanjena vjerojatnost u većoj mjeri će se ostvariti inherentnim fizikalnim karakteristikama i zakonitostima, a manje višestrukošću sigurnosnih sustava, što vodi u visoke investicijske troškove.

8 PROLIFERACIJA

Za razliku od tehničkih i ekonomskih pitanja koja se postavljaju kad se raspravlja o budućnosti nuklearne energetike i koja se rješavaju istraživanjem i razvojem, problem nuklearne proliferacije, tj. širenja nuklearnog oružja primarno je politički i treba biti razriješen političkim metodama. No, to ne umanjuje utjecaj na budućnost nuklearne energije. Nije sporno da se tehnologija za miroljubivo korištenje nuklearne energije može upotrijebiti za dobivanje nuklearnog eksploziva, iako početne i priznate nuklearne sile SAD, SSSR, Velika Britanija, Francuska i Kina nisu išle tim putem, jer je prva primjena nuklearne energije bila vojna. U Međunarodnoj studiji gorivnih ciklusa (International Fuel Cycle Evaluation, INFCE, 1978 –1980) prerada goriva i obogaćenje urana izdvojene su kao operacije ciklusa goriva osjetljive s obzirom na proliferaciju.

Prije 30 godina američki predsjednik Jimmy Carter zabranio je preradu istrošenog goriva u SAD, ali ta tehnička mjera zamišljena da spriječi proliferaciju izdvajanjem plutonija nije imala odziva u zemljama manje bogatima uranom od SAD. Osim pet nominalnih nuklearnih sila, medju kojima je Ruska Federacija u tom smislu sljednik SSSR-a, još dvanaest zemalja posjeduje instalacije za obogaćenje ili preradu goriva (Argentina, Belgija, Brazil, Indija, Italija, Izrael, Japan, Južna Afrika, Nizozemska, Njemačka, Pakistan, Sjeverna Koreja). Četiri od njih danas su prepoznate kao zemlje u posjedu nuklearnog oružja. U jednom periodu to je vrijedilo i za Južnu Afriku. Irački pokušaj proizvodnje plutonija završio je 1981. godine kada su izraelske zračne snage uništile irački reaktor Osiraq. Ozbiljna zabrinutost izazvana je gradnjom instalacija za obogaćenje

Chernobyl reactor lacked) reduces the probability of spreading radioactivity into the environment to approximately a value of 3 x 10^{-9}, or even lower. With a thousand reactors in operation, one core melting can be anticipated in a thousand years, and when it would occur, the probability of the spread of radioactivity into the environment would be less than one percent, owing to the protective building. This exceptional degree of safety is even acceptable for the most densely populated areas.

Nonetheless, work on improving nuclear safety continues within the framework of international projects such as the International Project on Innovative Nuclear Reactors and Fuel Cycles, INPRO, Generation IV reactors etc. However, the priority is not further reduction in CMP. Lower probability will be achieved to a greater extent through the inherent physical characteristics and laws, and to a lesser extent through multiple safety systems, which lead to high investment costs.

8 PROLIFERATION

Unlike technical and economic questions that are posed when the future of nuclear energy is discussed and are solved by research and development, the problem of nuclear proliferation, i.e. the spread of nuclear weapons, is primarily political and should be solved by political methods. However, this does not diminish the impact on the future of nuclear energy. It is indisputable that the technology for the peaceful use of nuclear energy can be used for obtaining a nuclear explosive, although the original and recognized nuclear powers, i.e. the United States, Soviet Union, Great Britain, France and China, did not take this path, because the first applications of nuclear energy were military. In the International Fuel Cycle Evaluation, INFCE, 1978 – 1980, the processing of fuel and enrichment of uranium were singled out as proliferation sensitive fuel cycles operations.

Thirty years ago, the American president Jimmy Carter prohibited the processing of spent nuclear fuel in the United States. However, this technical measure, conceived to prevent nuclear proliferation from the separation of plutonium, was not implemented in countries less rich in uranium than the United States. Except for the five nominal nuclear powers, among whom the Russian Federation is in this sense the heir to the former Soviet Union, another twelve countries possess installations for the enrichment or processing of nuclear fuel (Argentina, Belgium, Brazil, India, Italy, Israel, Japan, South Africa, the Netherlands, Germany, Pakistan and North Korea). Four of them are already recognized as countries that urana u Iranu, bez obzira na deklaracije da se radi samo o energetskom programu.

Ako se promatra budućnost u kojoj bi nuklearna energija dala bitan doprinos zamjeni fosilnih goriva u svim sektorima potrošnje, onda to znači višestruko veći broj reaktora, s nizom novih nuklearnih zemalja. Nastavljajući s praksom nacionalnih instalacija za preradu goriva i obogaćenjem urana to znači i povećanu opasnost nuklearne proliferacije, kao i ilegalnog prometa nuklearnim materijalima.

Pitanje dugoročne budućnosti nuklearne energije moglo bi se formulirati kao pitanje može li se gradnja nacionalnih instalacija za obogaćenje urana i preradu istrošenog goriva zamjeniti rješenjem otpornijim na proliferaciju, nekim oblikom međunarodnog servisa za opskrbu nuklearnim gorivom. Premda se u današnjoj međunarodnoj situaciji s otvorenim konfliktima na Bliskom Istoku, Dalekom Istoku, te izmedju Indije i Pakistana, napuštanje nacionalnih instalacija izgleda nedostižnom iluzijom. Optimizam se ipak može izvoditi iz toga što je alternativa gotovo sigurno klizanje u proliferaciju, nuklearni terorizam i katastrofu nuklearnog sukoba.

8.1 Ugovor o neširenju nuklearnog oružja – pokušaj kontrole nuklearne proliferacije

Najraniji pokušaj da se osigura od zloupotrebe nuklearne tehnologije bio je američki prijedlog u Ujedinjenim Narodima 1946. dok su eksplozije nad Hiroshimom i Nagasakijem još bile u svježem sjećanju. Prema tome prijedlogu, poznatom kao Lilienthal-Baruchov prijedlog, osnovala bi se agencija u okviru Ujedinjenih Naroda, International Atomic Development Agency, IADA, koja bi u svojim instalacijama obavljala najveći dio aktivnosti ciklusa goriva. No, Sovjetski Savez je tada već radio na svojoj atomskoj bombi (aktivirana 1949. godine) i suprostavio se prijedlogu.

Umjesto da svijet krene zajedničkim putem prema miroljubivom korištenju nuklearne energije, započela je trka u nuklearnom naoružanju. Ona je trajala sve do raspada Sovjetskog Saveza 1990. s time što je količina nuklearnog oružja dosegla brojke od više desetaka tisuća atomskih glava na svakoj strani, dovoljno za višestruko uništenje planeta.

Sredinom 80-tih godina u zraku su trajno bili bombarderi s nuklearnim oružjem, a desetine nuklearnih brodova i podmornica bile su razmještene na strateškim pozicijama, spremne za neposrednu akciju. Uz izvjesnu dozu sreće čovječanstvo je preživjelo taj nevjerojatan period.

possess nuclear weapons. At one period, this also applied to South Africa. Iraqi attempts to produce plutonium ended in 1981, when Israeli aerial forces destroyed the Iraqi reactor Osiraq. The construction of installations for the enrichment of uranium in Iran has aroused serious concern, despite a declaration that this merely involves the energy program.

If a future is considered in which nuclear energy would provide a significant contribution to the replacement of fossil fuels in all sectors of consumption, this would mean many times more reactors and a series of new nuclear countries. Continuing with the practice of national installations for the processing of spent nuclear fuel and uranium enrichment also signifies an increased threat of nuclear proliferation, as well as the illegal traffic of nuclear materials.

The question about the long-term future of nuclear energy could be formulated as the question of whether the construction of national installations for the enrichment of uranium and the processing of spent nuclear fuel can be replaced by a solution providing greater resistance to proliferation, some form of international service for the supply of nuclear fuel. Although in the current situation with open conflicts in the Near East, Far East, and between India and Pakistan, the abandonment of national installations appears to be a pipe dream. Optimism is possible because the alternative is nearly certain proliferation, nuclear terrorism and catastrophic nuclear conflict.

8.1 The Treaty on the Non-Proliferation of Nuclear Weapons – An Attempt to Control Nuclear Proliferation

The earliest attempt to insure against the abuse of nuclear technology was the American proposal at the United Nations in 1946, while the explosions in Hiroshima and Nagasaki were still fresh in memory. According to this proposal, known as the Lilienthal-Baruch Plan, an agency would be established within the framework of the United Nations, the International Atomic Development Agency, IADA, which would conduct most of the activity of the fuel cycle in its own installations. However, the Soviet Union was already working on its own atomic bomb, activated in the year 1949, and opposed this proposal.

Instead of the world embarking on a common path toward the peaceful use of nuclear energy, the nuclear arms race began. It lasted until the dissolution of the former Soviet Union in 1990, when there were many tens of thousands of atomic warheads on each side, enough to destroy the planet many times over.

Medjutim, ta situacija kao pozadina bitna je za razumijevanje kontrole širenja nuklearnog oružja. Do 1990. godine dvije nadmoćne nuklearne super sile kontrolirale su svaka svoj blok, dok je grupa nesvrstanih zemalja inzistirala na nuklearnom razoružanju.

U toj općoj atmosferi 1970. godine stupio je na snagu Ugovor o neširenju nuklearnog oružja, Non-Proliferation Treaty (NPT). NPT je ugovor izmedju grupe zemalja u posjedu nuklearnog oružja i zemalja koje ne posjeduju nuklearno oružje, ali žele iskorištavati nuklearnu energiju u miroljubive svrhe. Te zemlje obvezuju se ugovorom, (članak III.), isključivo na miroljubivu uporabu i prihvat međunarodnih kontrola od strane Međunarodne agencije za atomsku energiju MAAE (IAEA Safeguards). Nuklearne sile pak obvezuju se na stvarne korake prema nuklearnom razoružanju i na pomoć u usvajanju nuklearne tehnologije (članak IV.). Uravnotežene obveze dviju strana Ugovora rezultirale su u tome da je Ugovor o neširenju nuklearnog oružja postao jedan od najšire prihvaćenih međunarodih ugovora, sa 189 država potpisnica do konca 2006. godine.

Ugovor predviđa reviziju stanja primjene svakih pet godina. No, kako se iza 1970. godine utrka u nuklearnom naoružanju još samo intenzivirala, petogodišnje revizijske konferencije bile su mjesto sve oštrije kritike nenuklearnih članica prema nuklearnim silama. Čevrta revizijska konferencija 1990. godina bila je u nešto povoljnijoj atmosferi nakon sporazuma o uklanjanju nuklearnog oružja srednjeg dometa (Intermediate Nuclear Force Treaty) 1987. godine. U pozitivnijoj klimi nakon prestanka hladnog rata potpisani su izmedju SAD i Sovjetskog Saveza ugovori o smanjenju strateškog nuklearnog oružja, START I, 1991. godine, s redukcijom od polaznih 13 000 i 10 000 atomskih glava na oko 8 000 za svaku stranu. START II potpisan je 1993. godine i predviđa daljnju redukciju na 3 000 do 3 500 atomskih glava za svaku stranu.

Nakon raspada Sovjetskog Saveza najvećim dijelom je povučeno taktičko oružje malih snaga i malog dosega koje je izgubilo svoje mjesto u novim strateškim odnosima.

U toj povoljnijoj klimi na Petoj revizijskoj NPT konferenciji održanoj 1995. godine dogovoreno je produženje ugovora na neodređeno vrijeme. Nakon toga, pogoršanje opet nastupa kad je postalo vidljivo da bez obzira na ugovore START I i START II ipak ne dolazi do značajne redukcije strateškog oružja najveće snage. Također nije stupio na snagu ugovor o obustavi svih nuklearnih

During the mid 1980s, there were constantly bombers carrying nuclear weapons in the air, and dozens of nuclear ships and submarines were stationed at strategic positions, ready for direct combat. Humankind survived this incredible period with a certain amount of luck. However, this situation is the essential background for understanding the control of the proliferation of nuclear weapons. Until 1990, the two nuclear superpowers each controlled their own blocks, while the group of nonaligned countries was insisting upon nuclear disarmament.

Amidst this general atmosphere, in 1970 the Non-Proliferation Treaty, NPT, went into effect. The NPT is a contract among a group of countries that possess nuclear weapons and countries that do not possess nuclear weapons but want to use nuclear energy for peaceful purposes. These countries are obligated by Article III of the Treaty to use nuclear energy exclusively for peaceful purposes and accept international control by the International Atomic Energy Agency (IAEA Safeguards). The nuclear powers are obligated to take actual steps toward nuclear disarmament and contribute “to the further development of the applications of nuclear energy for peaceful purposes, especially in the territories of non-nuclear-weapon States” (Article IV). The balanced obligations of the two parties to the Treaty resulted in it becoming one of the most widely accepted international treaties, with 189 countries having signed it by the end of the year 2006.

The Treaty provides for a review of its operation every five years. However, since the nuclear arms race only intensified after 1970, the Review and Extension Conferences held every five years were places of increasingly sharp criticism of the nuclear powers by the non-nuclear members. The Fourth Review and Extension Conference, held in the year 1990, took place in a somewhat more favorable atmosphere following the Intermediate-Range Nuclear Forces Treaty of 1987, on the elimination of intermediate-range weapons. In the positive climate following the end of the Cold War, treaties were signed between the United States and the Soviet Union on the reduction of strategic nuclear weapons, START I, 1991, with reduction from the initial 13 000 and 10 000 atomic warheads on each side to approximately 8 000 on each side. START II, signed in 1993, called for further reductions of 3 000 – 3 500 atomic warheads on each side.

After the dissolution of the Soviet Union, for the most part tactical weapons of low power and range that had lost their places in the new strategic relationship were withdrawn.

testova (Comprehensive Test Ban Treaty, CTBT) potpisan1996.

Na Šestoj revizijskoj NPT konferenciji 2000. godine nuklearne sile svjesne svojih neispunjenih obveza deklariraju svoju predanost procesu nuklearnog razoružanja (unequivocal commitment). No, u idućih pet godina do sljedeće, posljednje Sedme revizijske NPT konferencije 2005. godine nije bilo napretka niti u redukciji naoružanja niti u stupanju na snagu zabrane testova (CTBT), kao ni Ugovora o zabrani proizvodnje materijala za nuklearno oružje, Fissile Materials Cut of Treaty, FMCT, pa je ova konferencija završila bez dogovora i zaključaka, u neizvjesnosti, s pesimističkim predviđanjima glede budućnosti.

Tu su relevantna upozorenja Direktora MAAE dr. Muhameda ElBaradeia iz kolovoza 2006. godine [15] prilikom desete godišnjice potpisa Ugovora o zabrani nuklearnih testova CTBT koji još uvijek nije stupio na snagu, iako ga je potpisalo 170 zemalja, a ratificiralo 135, pa dakle odražava želju većine zemalja. Dr. ElBaradei ističe da je NPT utemeljen na dva stupa, prvi stup je kontrola proliferacije prema članku III. Ugovora. Tu je MAEE načinila mnogo, od 1970. godine razvijena je kontrolna operativa i regulativa, ugovore o kontroli ratificiralo je 162 potpisnice NPT-a, a njih 78 i kasnije formulirane (od 1997. godine) Dodatne protokole kojima se osigurava viši stupanj sigurnosti od proliferacije. Drugi stup Ugovora o neširenju nuklearnog oružja je članak VI, obveza nuklearne petorke da učine stvarne korake prema uklanjanju nuklearnog oružja. Dr. ElBaradei navodi da u 2006. godini još uvijek postoji oko 27 000 atomskih glava. No, nije samo problem što nije došlo do bitnog napretka u uklanjanju nuklearnog oružja. Ni deset godina nakon potpisa na snagu nije stupio Ugovori o zabrani nuklearnih pokusa CTBT, a za zabranu proizvodnje materijala za nuklearno oružje, FMCT još nema suglasnosti za početak pregovora. Ta su dva ugovora bitna za zaustavljanje daljnjeg razvoja i proizvodnje nuklearnog oružja. Izostaje potvrda nuklearnih sila da one doista imaju namjeru ispuniti svoju obvezu prema NPT i odreći se nuklearnog oružja. U takovoj situaciji dr. ElBaradei naslućuje mogućnost erozije NPT- a, smatrajući da se međunarodni sustav kontrole proliferacije nalazi na opasnoj prekretnici.

8.2 Multilateralni pristupi

Zadržavanjem velikog dijela strateškog nuklearnog arsenala dviju nuklearnih supersila gotovo dvadeset godina po završetku hadnog rata, nuklearno oružje pretvoreno je u svojevrsni statusni simbol i prepoznato kao poluga svjetske dominacije. Ono postaje atraktivno ili izaziva obrambenu reakciju, a

In this favorable climate, at the Fifth NPT Review and Extension Conference, held in the year 1995, the extension of the Non-Proliferation Treaty for an indefinite period of time was agreed upon. After this, the situation worsened when it became evident that despite START I and START II, there was not going to be any significant reduction in the strategic weapons of the superpowers. Furthermore, the Comprehensive Test Ban Treaty, CTBT, which was signed in the year 1996, did not go into effect.

At the Sixth NPT Review and Extension Conference, held in the year 2000, the nuclear powers, aware of their unfulfilled obligations, declared their unequivocal commitment to the nuclear disarmament process. However, during the subsequent five years until the Seventh NPT Review and Extension Conference in 2005, there was no progress in the reduction of armaments, the going into effect of the Comprehensive Test Ban Treaty (CTBT) or the going into effect of the Fissile Material Cut-Off Treaty, FMCT, to ban the production of fissile material that can be used for nuclear weapons. Thus, the Seventh NPT Review and Extension Conference ended without consensus or conclusions, in uncertainty, amidst pessimistic forecasts for the future.

Relevant warnings were made by the General Director of the International Atomic Energy Agency (IAEA), Dr. Mohamed ElBaradei, in August 2006 [15] on the occasion of the tenth anniversary of the Comprehensive Test Ban Treaty opening for signature, which still has not gone into force although it has been signed by 170 countries and ratified by 135, thereby expressing the desire of the majority of countries. Dr. ElBaradei points out that the Nuclear Non-Proliferation Treaty had two “legs,” the first of which was non-proliferation according to Article III of the Treaty. The IAEA had done much in this regard, having established a system of verification in 1970. An arms control treaty was ratified by 162 signers of the Non-Proliferation Treaty, and 78 of them ratified the subsequently formulated (1997) Additional Protocol, which assures a higher degree of protection from proliferation. The other “leg” of the Nuclear Non-Proliferation Treaty is Article VI, a commitment by the five countries with nuclear weapons to take actual steps towards nuclear disarmament. Dr. ElBaradei notes that in the year 2006, there were still 27 000 nuclear warheads in existence. However, the problem was not only that there had been no significant progress in the elimination of nuclear weapons. Even ten years after the Comprehensive Test Ban Treaty had been opened for signature, it had not gone into effect, and for the Fissile Material Cut-Off Treaty, FMCT, there was still no agreement on a mandate to start negotiating. These two treaties are essential to halt the continued development and production of nuclear weapons. What is missing is u svakom slučaju stimulira proliferaciju. Nuklearne sile koje se ne razoružavaju, niti su spremne odreći se daljnjeg razvoja nuklearnog oružja nisu u poziciji, ni moralno ni legalno, pozivati se na NPT u nastojanju da zaustave nuklearne razvoje u nenuklearnim zemljama. Pokušava se stoga novim pristupom gdje se pojedinim zemljama nude ugovori za opskrbu nuklearnim gorivom, ukoliko odustanu od vlastitih instalacija za obogaćenje urana.

Zemlja koja dobavlja gorivo pri tom nema obveze vlastitog razoružanja, a zemlja primalac odriče se prava koje je imala po članku IV. ugovora NPT. Za razliku od sustava NPT koji je imao gotovo univerzalan prihvat svojom ravnotežom obveza dviju strana, u tzv. Multilateralnom sustavu nuklearne zemlje nemaju obveze razoružanja. Vrlo je mala šansa da takav sustav bude univerzalno prihvaćen poput NPT-a. Nije nemoguće da će takav sustav dobave goriva biti pogodan nekim zemljama, ali ga sigurno neće prihvatiti one zemlje koje kao i postojeće nuklearne sile žele posjedovati taj statusni simbol. Multilateralne pristupe analizirala je i MAAE [16]. Međutim, jedno univerzalno prihvaćanje odricanja od nacionalnih instalacija za obogaćenje urana i preradu goriva zamislivo je samo ako bi se sve postojeće instalacije, dakle i one u nuklearnim zemljama, izuzele iz nacionalnog upravljanja i došle pod jurisdikciju i nadzor međunarodne organizacije poput MAAE, drugim riječima ako bi se vratili na nešto slično početnom pokušaju iz 1946. godine. No, dok je internacionalizacija gorivnog ciklusa dugoročnija budućnost, koraci nuklearnih zemalja potpisnica NPT u pravom smjeru bili bi oni kojim bi one pokazale namjeru ispunjavanja svojih obveza po članku VI, a to su prihvat zabrane testova, tj. ugovora CTBT i zabrane proizvodnje materijala za nuklearno oružje (FMCT).

confirmation from the nuclear powers that they truly intend to fulfill their obligations toward the Nuclear Non-Proliferation Treaty and relinquish their nuclear weapons. In such a situation, Dr. ElBaradei senses possible erosion of the NPT, in that the international system of the control of nonproliferation could be at a dangerous turning point.

8.2 Multilateral Approaches

The two nuclear superpowers, by retaining a large portion of their strategic nuclear arsenal for nearly twenty years after the end of the Cold War, have transformed nuclear weapons into a type of status symbol that is recognized as a lever of world domination. Nuclear weapons are becoming attractive or provoke a defensive reaction, and in any case stimulate proliferation. The nuclear powers are not disarming, are not ready to relinquish the further development of weapons, and are not in a moral or legal position to invoke the NPT in their attempts to stop nuclear development in non-nuclear countries. They are, therefore, attempting a new approach, whereby they offer individual countries contracts for the supply of nuclear fuel if they relinquish their own installations for uranium enrichment.

Accordingly, the country that supplies nuclear fuel is not required to disarm, and the recipient country relinquishes the rights which it had pursuant to Article IV of the Nuclear Non-Proliferation Treaty. Unlike the system of the NPT, which had almost universal acceptance with its balanced obligations between the two sides, the nuclear countries are not obligated to disarm in the so-called multilateral system. There is very little chance that such a system would be universally accepted, as was the NPT. It is not impossible that such a system for the supply of nuclear fuel will be favorable for some countries, but it certainly will not be accepted by those countries which, like the existing nuclear powers, want to possess this status symbol. Multilateral approaches have also been analyzed by the IAEA [16]. However, the universal acceptance of the relinquishment of national installations for uranium enrichment and processing spent nuclear fuel is only conceivable if all the installations, including those in the nuclear countries, are removed from national administration and come under the jurisdiction and supervision of an international organization such as the IAEA, i.e. if they were to return to something similar to the attempt begun in the year 1946. However, while the internationalization of the fuel cycle is still in the distant future, it would be a step in the right direction by the nuclear countries that are signers of the NPT to demonstrate their intentions to fulfill their obligations pursuant to Article VI, by accepting the test ban, i.e. the Comprehensive Test Ban Treaty, and by prohibiting the production of materials for nuclear weapons according to the Fissile Material Cut-Off Treaty.

9 ZAKLJUČAK

Nakon pet desetljeća postojanja nuklearna energetska industrija je sazrijela, a njen udio u opskrbi električnom energijom na svjetskoj razini je 16 %. Trendovi u planiranju energetike ponovo ju čine atraktivnom opcijom, te mnogi predviđaju daljnji rast sadašnjeg udjela u opskrbi. Zalihe urana dostatne su da omoguće razvoj čak i u najoptimističnijem scenariju. Tehnološki razvoj i akumulirano iskustvo učinili su današnje reaktore pogonski pouzdanim i ekonomičnim, a sigurnost je dosegla vrlo visok nivo. Proizvodnja velikih količina električne energije bez emisija stakleničkih plinova svakako je jedan od glavnih aduta nuklearne tehnologije.

Unatoč značajnom napretku, najavljena nuklearna renesansa sa sobom nosi i značajne izazove za nuklearnu industriju. Prije svega sadašnji dobri pokazatelji sigurnosti, pouzdanosti i ekonomičnosti pogona reaktora moraju se nastaviti i u budućnosti. Liberalizacija tržišta električnom energijom mijenja preference investitora i čini ih više osjetljivim na rizike. Zbog toga će nuklearna industrija morati uložiti značajne napore za snižavanje troškova i skraćivanje rokova izgradnje nuklearnih elektrana. Iako je pitanje zbrinjavanja nisko i srednje radioaktivnog otpada riješeno, potrebno je uložiti dodatne napore kako bi se ponudio adekvatan odgovor i na pitanje zbrinjavanja visokoradioaktivnog otpada. Značajno širenje nuklearne energije nesumnjivo će povećati i opasnost od proliferacije nuklearnih materijala, te je i u tom aspektu potrebno uložiti značajne napore. Očekuje se da će reaktori naprednog dizajna (AP1000, EPR, ABWR) s karakteristikama pasivne sigurnosti, sniženim investicijskim i pogonskim troškovima pružiti odgovore na većinu navedenih problema.

Nuklearna tehnologija, kao i svaka druga uostalom, ima određene predosti i nedostatke. Današnje okolnosti ponovno favoriziraju prednosti, te su sve glasniji glasovi da se na nuklearnu tehnologiju mora računati kao bitnu sastavnicu energetskog miksa budućnosti.

9 CONCLUSION

After five decades that the nuclear power industry has been in existence, it has matured and its share in the world energy supply is 16 %. Trends in energy planning once again make it an attractive option and many predict the continued growth of its share in the total electricity supply. Uranium reserves are sufficient to permit development, even in the most optimistic scenario. Technological development and accumulated experience have made today’s reactor plants reliable and economical. A very high level of safety has been achieved. The production of large quantities of electrical energy without the emission of greenhouse gases is certainly one of the most attractive attributes of nuclear technology.

Despite significant advancement, the heralded nuclear renaissance also implies challenges for the nuclear industry. First of all, today’s good safety indices and reliability, together with the cost effectiveness of reactor plants, must also continue in the future. The liberalization of the electricity market changes the preferences of investors and makes them more vulnerable to risks. Therefore, the nuclear industry must invest considerable efforts in reducing costs and shortening the time required for the construction of nuclear power plants. Although the question of the disposal of low-level and medium-level radioactive wastes has been solved, it is necessary to invest additional efforts in order to provide an adequate response to the question of the disposal of high-level radioactive wastes. The significant spread of nuclear energy will undoubtedly increase the threat of the proliferation of nuclear materials, and it is also necessary to invest considerable efforts in this aspect. It is anticipated that reactors of advanced design (AP 1000, EPR and ABWR), characterized by passive safety, reduced investment costs and reduced operational costs, will provide responses to the majority of the problems presented.

Nuclear technology, like any other technology, has certain advantages and disadvantages. Today’s circumstances once again favor the advantages, and it is increasingly apparent that it is necessary to count on nuclear technology as an essential component of the energy mix of the future.

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