JET

Journal of ENERGY TECHNOLOGY

FACULTY OF ENERGY TECHNOLOGY

Volume 1 / Issue 1
NOVEMBER 2008
www.fe.uni-mb.si/jet

JOURNAL OF ENERGY TECHNOLOGY

Ustanovitelji / FOUNDERS

Fakulteta za energetiko, UNIVERZA V MARIBORU /

FACULTY OF ENERGY TECHNOLOGY, UNIVERSITY OF MARIBOR

Izdajatelj / PUBLISHER

Fakulteta za energetiko, UNIVERZA V MARIBORU /

FACULTY OF ENERGY TECHNOLOGY, UNIVERSITY OF MARIBOR

Tehniška podpora / TECHNICAL SUPPORT

Janko OMERZU

Sonja NOVAK

Izhajanje revije / PUBLISHING

Revija izhaja štirikrat letno v nakladi 300 izvodov. Članki so dostopni na spletni strani revije - www.fe.uni-mb.si/JET .

The journal is published four times a year. Articles are available at the journal home page - . www.fe.uni-mb.si/JET .

Lektoriranje / Language Editing

Terry T. JACKSON

Produkcija / PRODUCTION

Vizualne komunikacije comTEC d.o.o.

Oblikovanje znaka revije / LOGO DESIGN

Andrej PREDIN

Prva številka revije JOURNAL OF ENERGY TECHNOLOGY

Le malo ljudi je verjelo, da bo ta zahteven projekt uresničen. Zato smo še toliko bolj veseli, da nam je kljub skromnim izdajateljskim izkušnjam in omejenim sredstvom uspelo.

The first number of the JOURNAL OF ENERGY TECHNOLOGY

Only a few people have believed that this demanding project could be realized with lack of experience and limited founding. We are very happy that we succeeded mostly with willingness and enthusiasm.

Krško, December 2008

Andrej PREDIN

Table of Contents / Kazalo

JET Volume 1 (2008), p.p. 7 - 20

Issue 1, November 2008

www.fe.uni-mb.si/JET

SLOW BREEDING AND TRANSMUTATION PROCESS IN LOW FLUX REACTOR

POČASNA TRANSMUTACIJA IN KONVERZIJA ^{238}U V ^{235}U V REAKTORJIH Z ZELO NIZKIM FLUKSOM

Tomaž Žagar [1,2]
[1] GEN energija, d.o.o.
Cesta 4. julija 42, SI-8270 Krško, Slovenia

[2] Jožef Stefan Institute
Jamova 39, SI-1000 Ljubljana, Slovenia
tomaz.zagar@ijs.si

Joseph Magill
European Commission, Joint Research Centre, Institute for Transuranium Elements
P.O. Box 2340, D-76125 Karlsruhe, Germany
joseph.magill@cec.eu.int

Keywords: breeding and transmutation process, low flux reactor, natural reactor (Up to 10 keywords)

Abstract

This work presents the physics of self-sustained critical reactor operating at very low constant neutron flux. It is shown, that such reactor is a breeder and a clean reactor, not producing any higher actinides. Fossil fission reactors in Gabon were found to be natural analogues of such reactors. On the basis of these results, the concept of active repository is proposed and studied. It is shown that this concept has a very limited practical application.

Povzetek

Članek predstavlja fiziko kritičnih reaktorjev, ki delujejo pri zelo nizkem nevtronskem fluksu, veliko pod nivoji, ki se uporabljajo v komercialnih reaktorjih. V jedrskem reaktorju, ki deluje pri tako nizkem nevtronskem fluksu poteka poseben proces konverzije, v katerem iz oplodnega ^{238}U nastaja novo jedrsko gorivo ^{235}U. Proces je mogoč, ker pri nizkem fluksu reakcijska hitrost razpada ^{239}Pu prevlada nad reakcijsko hitrostjo zajetja nevtronov in cepitve v ^{239}Pu. Zaradi tega je reaktor, ki obratuje pri ekstremno nizkih fluksih "čist" reaktor, ki praktično ne proizvaja visokih aktinidov. V naravi se je takšen proces odvijal v fosilnem reaktorju v Gabonu. V prispevku je teoretično preučena tudi možnost izrabe omenjenega fizikalnega procesa v tako imenovanem aktivnem odlagališču, v katerem bi dolgoživi radioaktivni odpadki v obliki višjih aktinidov zgorevali v kratkožive radioaktivne odpadke. Članek prikaže, da je takšno odlagališče v praksi neuporabno.

----

1. INTRODUCTION

Fossil reactors found in the Oklo region in Gabon [1][2] are a fascinating natural phenomenon. They were extensively studied from several different aspects including as diverse fields as the verification of variability of the long-term fundamental physical constants to storage of nuclear wastes in geological environments. From the clear isotopic signatures extracted from the fossil reactors a reconstruction and estimation of the main physical properties of these reactors was possible. It was estimated that these reactors were critical in extremely long time scales of 100 000 yr (up to 150 000 yr). The fact that natural reactors did not explode and dissipate themselves right after they went critical was evidently due to some negative feedback mechanism. Some suggestions indicate that this self-regulation has included water.

In one particular case one reactor consumed more than 5 tons of ^{235}U and released 15 GWyr in this time [3]. Total effective neutron fluence was up to 10^{21} n/cm^2. However; due to extremely long operation times the average flux and average power of these reactors was extremely small. The average power of one reactor was only about 100 kW, and average flux was only about 10^8 n/cm^{2}s to 10^9 n/cm^{2}s. In this paper we will study transmutation and breeding properties of reactors running at such low neutron fluxes.

2. LOW FLUX REACTOR PHYSICS

Low flux reactor (LoFR) is a nuclear system running at low neutron flux for a prolonged period of time in the terms of human life. In this work the concept of the LoFR is studied in connection with geological phenomena in Earth's ancient geological history. Fossil reactor in Oklo, Gabon is one example of natural LoFR accepted by scientific community; however it might not be the only one. Besides very low power levels, there are two other distinguished properties of LoFR. These two properties are first, their breeding capability and second, their "clean" nature in regard to the production of minor actinides (e.g. Np, Am, Cm). We will describe both of them briefly in the following chapters.

2.1 Breeding Process in LoFR

The sequence of the neutron capture and decay reactions in LoFR breeding process differs significantly from the well known and established breeding process in typical power reactors. In the LoFR breeding process (presented in the Figure 1) the first part of the reaction chain is the same as in the traditional breeding. The neutron capture reaction in ^{238}U leads to ^{239}Pu over two short-lived isotopes of ^{239}U and ^{239}Np (with half-lives of 23.45 min and 2.36 d, respectively [4]). However; if the neutron flux is below certain critical level ϕ_c, then the decay of ^{239}Pu to ^{235}U will prevail over neutron capture reaction leading to ^{240}Pu and other minor actinides (MA) with longer half-lives. This critical flux is of course spectrum dependant. The critical flux is defined by the following condition:

$$\sigma_{nc}\phi_c = \lambda_d; \qquad \phi_c = \lambda_d / \sigma_{nc} \tag{1}$$

Where σ_{nc} is neutron capture cross-section of ^{239}Pu and λ_d is decay constant of ^{239}Pu. Half-life of ^{239}Pu is 24.4 kyr (7.7×10^{11} s) and this gives us λ_d of 9×10^{-13} n/s. For the neutron capture cross-sections under question (in LWR flux 58.7 b and 0.56 b in FR) we get the following critical flux levels: 1.5×10^{10} n/cm^{2}s in LWR spectrum and 1.6×10^{12} n/cm^{2}s in FR spectrum.

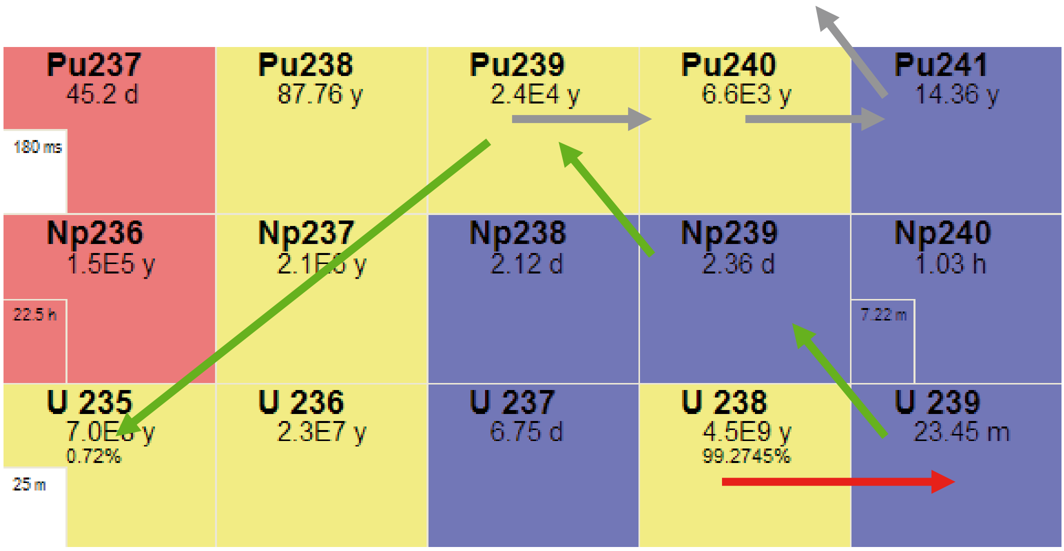

***Figure 1**: Part of the nuclides chart with a schematic presentation of a Low Flux Reactor breeding process. Red arrow presents neutron capture reaction in uranium, green arrows stand for natural decay (beta or alpha). Traditional chain of reactions in modern reactors is indicated with gray arrow from plutonium (nuclear data taken from Nuclides.net [4]).*

As long as the flux in a LoFR is well below ϕ_c (e.g. below 10^{12} n/cm^{2}s for fast spectrum) the above mentioned breeding process leads to a constant enrichment of uranium under long low-flux irradiation as it can be seen on Figure 2. This figure shows enrichment of uranium under constant neutron irradiation with two different flux spectra as a function of time. We have considered hard neutron spectrum similar to neutron spectrum in a fast reactor (FR) and thermalized spectrum similar to spectrum in light water moderated reactors (LWR). In both cases different initial conditions were considered representing the enrichment of natural uranium at different times of Earth's geological history. Three different starting enrichments were taken into account, the first enrichment is 10.5 %, corresponding to natural enrichment approximately 3 Byr before present (BP) [5]. The second enrichment is 3.7 % for 2 Byr BP and the last one is current enrichment of natural uranium 0.72 %. Natural uranium enrichment reduction due to decay alone is quite slow on a Myr scale. But we can see that the enrichment in LWR flux reaches constant value of 1.35 % due to LoFR breeding after approximately 3 Myr. This enrichment is flux dependant, as will be demonstrated later.

The rate of enrichment changes in fast flux is slower due to smaller cross-sections. However, the final equilibrium enrichments are significantly higher and reach levels between 11 and 12 %. Time evolution of the uranium enrichment in fast flux experienced in metal uranium reactors is presented in Figure 3. Time interval required for final approach to a constant enrichment of uranium in metal fuel depends on the initial enrichment of the fuel. Constant enrichment is achieved after 30 to 80 million years after the initial irradiation. Exact equilibrium uranium

----

enrichment in LoFR depends on neutron flux level. In a constant neutron flux of 10^9 n/cm^{2}s the equilibrium enrichment is 11.66 %. Results of study of equilibrium enrichments values for different flux levels are presented in Table 1. Equilibrium levels in smaller fluxes are smaller. For neutron flux of 10^7 n/cm^{2}s the equilibrium enrichment is only 5.68 %. The time required for equlibirum to be achieved is significantly longer in lower fluxes.

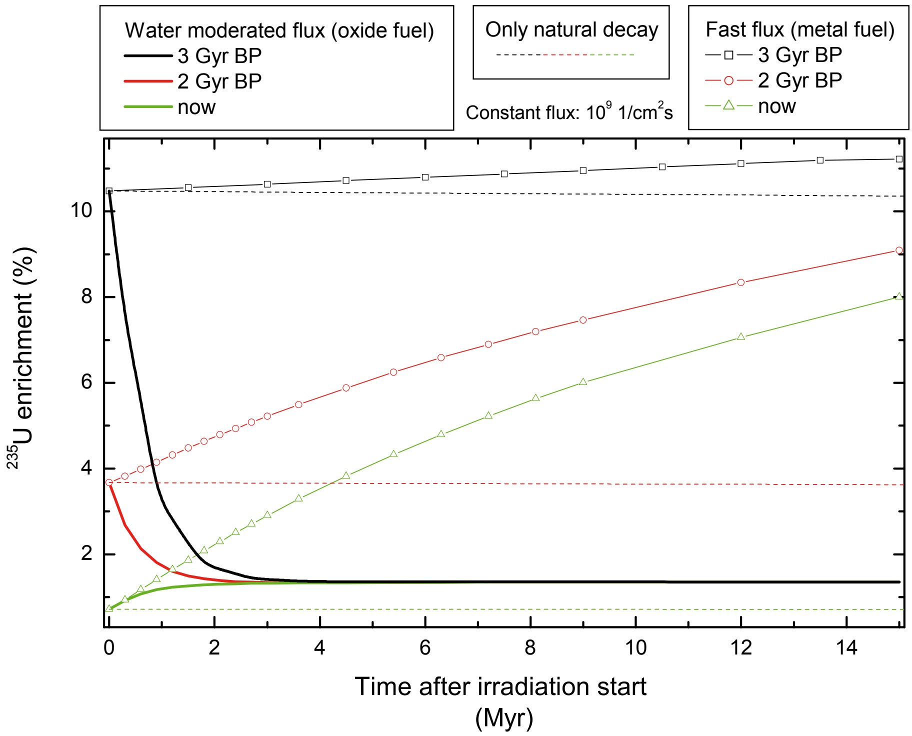

Figure 2: *Enrichment of uranium as a function of time under constant irradiation with 10^9 n/cm^{2}s neutron flux. Thick lines represent results with water moderated spectrum. Thin lines with symbols indicate results with fast spectrum. In both cases different initial conditions were considered representing the enrichment of natural uranium at different times of Earth's geological history. Dashed lines show enrichment as a function of natural decay.*

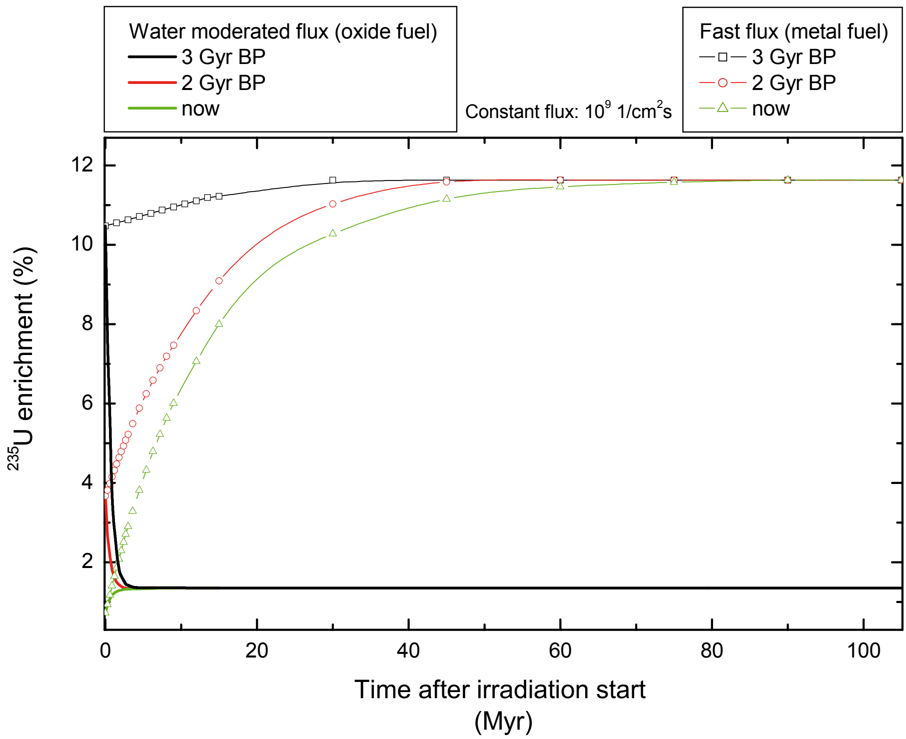

***Figure 3**: Enrichment of uranium as a function of time under constant irradiation with 10^9 n/cm^{2}s neutron flux. Approach to a constant enrichment of uranium in metal fuel form can be seen. Constant enrichment is achieved after 30 to 80 million years after the initial irradiation. Thick lines represent results with water moderated spectrum. Thin lines with symbols indicate results with fast spectrum. In both cases different initial conditions were considered representing the enrichment of natural uranium at different times of Earth's geological history.*

Natural uranium reactors found in Oklo, Gabon, were operating at similar low flux levels [10]. LoFR breeding process might play important role in the operation of natural reactors. LoFR breeding in a natural uranium areas within geological formations could prolong the operation of such LoFR for long period of time (several kyr or even several Myr) as was already described by Herndon [6][7] and Seifritz [8]. Signs or indication of prolonged natural reactor operation (150 kyr) were also found in Oklo natural fossil fission reactors [9].

2.2 LoFR is a Clean Reactor

After long time uranium enrichment under constant flux irradiation reaches a certain equilibrium levels. For fast spectrum the enrichment is stable at values around 11 % and for moderated systems it is stable around 1.5 %. This enrichment is slightly flux dependent as can be seen in Table 1. The calculations presented here were done with the ORIGEN code [11]. We used cross-sections for fast sodium cooled reactor with metal fuel for FR flux calculations and cross-sections for pressurised water reactor with oxide fuel for LWR calculations. In addition to the equilibrium enrichment we calculated also concentrations of other transuranium isotopes. Of all those isotopes only ^{237}Np and ^{239}Pu can be found in significant concentrations. Other transuranium isotopes are present only in traces. The results of the calculations are presented as ratios of different isotopes relative to ^{238}U. Only data for uranium, plutonium, neptunium, ^{241}Am and ^{242}Cm isotopes are presented. The concentrations of all other MA are much smaller. Even concentrations of other curium isotopes with longer half-lives (e.g. ^{244}Cm or ^{245}Cm) are much smaller. The ratio of ^{239}Pu in this system is directly related to neutron flux levels. LoFR breeding is extremely slow process. Times needed to reach equilibrium isotope concentrations are between million and billion years. Approximate time scales needed to reach equilibrium concentrations for particular flux levels are presented in Table 1. These time values indicate the time scales of processes involved and are connected to ^{239}Pu decay and ^{235}U burnup processes. All other actinides reach equilibrium values significantly faster (on a time scale well below 1 Myr). For comparison we have added also typical concentrations of transuranium isotopes in a spent fuel material from a commercial PWR power plant. Data for spent fuel is typical for fuel burnued to a burnup of 33 000 MWd/MTU.

***Table 1**: Equilibrium ^{235}U enrichment; ^{239}Pu to ^{238}U ratio; and three other MA to ^{238}U ratios as a function of neutron flux level. Calculations were performed for fast (metal fuel) and thermalized (oxide fuel) neutron spectrum. Approximate times needed to reach those equilibrium concentrations is also given for different flux levels. Typical concentration of transuranium isotopes in spent fuel from commercial PWR is added for comparison.*

Fast flux [n/cm^{2}s]	**Time [Myr]**	**^{235}U enr. [%]**	**^{239}Pu/ ^{238}U**	**^{237}Np/ ^{238}U**	**^{241}Am/ ^{238}U**	**^{242}Cm/ ^{238}U**
10^7	800	5.68	3.16×10^{-6}	1.8×10^{-6}	4.6×10^{-19}	1.3×10^{-28}
10^8	200	9.99	3.16×10^{-5}	3.9×10^{-5}	4.4×10^{-16}	1.2×10^{-24}
10^9	50	11.66	3.15×10^{-4}	2.8×10^{-3}	4.6×10^{-13}	1.3×10^{-20}
Thermal flux [n/cm^{2}s]						
10^7	150	1.49	9.75×10^{-6}	1.7×10^{-5}	7.0×10^{-14}	1.5×10^{-21}
10^8	25	1.53	9.58×10^{-5}	6.3×10^{-4}	6.8×10^{-11}	1.5×10^{-17}
10^9	4	1.35	8.16×10^{-4}	3.6×10^{-3}	5.5×10^{-8}	1.2×10^{-13}
Spent fuel from PWR						
n/a	n/a	≈ 1	$\approx 6\times10^{-3}$	$\approx 7\times10^{-4}$	$\approx 5\times10^{-4}$	$\approx 5\times10^{-9}$

We should keep in mind, that the minimum enrichment of infinite metal uranium needed for criticality in fast flux is approximately 9 %. So we can see from the above table that natural LoFR without moderation cannot operate at flux levels lower than 10^8 n/cm^{2}s. Minimum enrichment of uranium in well moderated light water configuration needed for criticality is significantly smaller - it is between 1 and 2 %. So it is theoretically possible for a natural LoFR to operate continuously, if some natural mechanism would retain the flux levels constant trough all the millions of years. One such mechanism could be water temperature in the reactor as was proposed and shown lately for the Oklo reactors [2]. Even if this breeding phenomena in natural uranium fields might be very interesting for physical and philosophical community, it's practical consequences for the modern world are probably very small. However it's influence on public acceptance in future might become more important.

On the other hand, the fact that MA concentrations in LoFR are very small might have a practical application in our world. Not only MA concentrations, also ^{239}Pu concentrations in LoFR are smaller than concentrations found in typical spent fuel from commercial reactors. This can be explained as follows. Neutron flux in such a reactor is too small for several consequent neutron capture reactions in plutonium needed to generate higher MA. We can see that concentrations of Pu in such a reactor are very small (below 0.1 % for a flux of 10^9 n/cm^{2}s). Equilibrium concentrations of Pu are increasing linearly with increasing flux level. ^{237}Np concentrations in LoFR during continuous operation are somewhat higher. Other minor actinide concentrations are negligible. Due to this absence of minor actinides the LoFR can be called a "clean" reactor. The concentration of MA is still negligible even if we normalise both reactors to the same energy output as can be seen in Table 2. Due to low power density we need an enormous amount of uranium to generate significant amounts of energy in the LoFR. However, Pu and Np masses are still low and other MA can only be found in traces.

***Table 2**: Comparison of masses in equilibrium (only uranium and minor actinides) for typical PWR and fast LoFR normalised to 1 MW thermal output. PWR: fresh enrichment was 3.2%, burnup is 33 000 MWd/MTU. LoFR: in equilibrium at fast flux 10^9 n/cm^{2}s.*

	PWR	**LoFR**
U	25 kg	5×10^4 kg
Pu	150 g	1500 g
Np	17.5 g	900 g
Am	12.5 g	10^{-13} g
Cm	1.25×10^{-4} g	10^{-22} g

----

3. LOW FLUX REACTOR AS AN ACTIVE REPOSITORY?

The question we address in this chapter is: “Is it possible to harness the LoFR as a clean MA burner?” To study this option we imagined a manmade underground reactor – active repository – running at low flux levels for very long times. The idea of long-term underground reactor is not new. A different underground reactor concept was first proposed by Edward Teller [12]. His concept of self-breeding manmade thorium-uranium candle reactor [13] is focused around the need for safe long-term energy production source. Its thermal power would be around 2 GW and it would run for a period of 30 yr without refuelling. Since the main objective of our active repository is not energy production, its neutron flux levels and energy production densities would be several orders of magnitude smaller, and it should run for significantly longer time periods.

To simulate a LoFR as an active repository, calculations were performed for a period of 2000 years. The assumptions in the calculations were as follows: the critical LoFR was loaded with 10 % enriched uranium in metal form and 1 % of one selected long-lived actinide. We loaded LoFR with either ^{237}Np, ^{239}Pu, ^{244}Cm, or with mixture of Am isotopes found in spent fuel. All calculations were normalized to one metric ton of uranium metal (MTU). Introduction of a small amount of actinides does not change the criticality or flux characteristics, which remained typical for a fast reactor (k_{inf} of the system remained a little above unity). This LoFR was then left to operate at constant flux for 2000 yr. After this time the decrease of actinide mass in the system was observed and compared to natural decay of those actinides in the same period of time. The transmutation of selected long-lived actinides in LoFR is very small. It is almost overwhelmed by the natural decay. For the purpose of this analysis we defined a LoFR transmutation capability TC_{LoFR} after time t as:

$$TC_{LoFR}(t) = \frac{m_{LoFR}(t)}{m_D(t)} \qquad (2)$$

Where m_{LoFR} is the mass of the actinide after time t inside the LoFR, and m_D is the mass of the same actinide isotope reduced only by the natural decay in the time t. If the TC_{LoFR} is one, then the transmutation in the LoFR has no effect at all. If the TC_{LoFR} is above one, then LoFR is reducing the radioactivity of this isotope. Calculations were repeated for two different flux levels and are presented in Tables 3 and 4. Transmutation capability of LoFR for different isotopes is presented in the last column of those tables.

***Table 3**: Transmutation capability of a fast LoFR (not moderated) at a flux 10^9 n/cm^{2}s.*

Actinide	Initial mass [g]	m_{LoFR}(2000 yr) [g]	m_D(2000 yr) [g]	TC_{LoFR}(2000 yr)
^{237}Np	10 000	9 992	9 993.5	1.0002
^{239}Pu	10 000	9 455	9 441.6	0.9986
^{241}Am	8 000	323.7	324.36	1.0020
^{243}Am	2 000	1 657	1 657.3	1.0002
^{244}Cm	10 000	217.6 (100y)	217.77 (100y)	1.0008 (100y)

***Table 4**: Transmutation capability of a fast LoFR (not moderated) at a flux 10^{11} n/cm^{2}s.*

Actinide	Initial mass [g]	m_{LoFR}(2000 yr) [g]	m_D(2000 yr) [g]	TC_{LoFR}(2000 yr)
^{237}Np	10 000	9 890	9 993.5	1.0105
^{239}Pu	10 000	10 090	9 441.6	0.9357
^{241}Am	8 000	319.7	324.36	1.0153
^{243}Am	2 000	1 644	1 657.3	1.0081
^{244}Cm	10 000	217.6 (100y)	217.77 (100y)	1.0008 (100y)

Transmutation capability of our active repository with fast flux is extremely small. It is smaller than 1 % for all isotopes in flux 10^9 n/cm^{2}s. Even if we increase flux to 10^{11} n/cm^{2}s the transmutation capability of LoFR remains small. Even now the highest TC_{LoFR} is only 1.5 % for ^{241}Am. Since the half-life of ^{244}Cm is only 18.11 yr, we calculated TC_{LoFR} for this isotope after 100 yr. In both tables we can also see an example of "negative" transmutation (e.g. $TC_{LoFR} < 1$) or breeding. This is consistent with predictions found in Table 1. The concentration of ^{239}Pu isotope is increasing towards its equilibrium value at given flux.

Since flux 10^{11} n/cm^{2}s is already over the critical ϕ_c for fast LoFR, we recalculated the active repository with this flux levels using a thermal PWR flux spectrum. Uranium enrichments needed in water moderated PWR flux are smaller than in fast flux and added actinide concentrations have a higher influence on k_{inf}, but other calculation assumptions were kept the same as for fast flux. Calculations for this configuration are presented in Table 5. In the thermal LoFR minor actinides are burned faster and the required uranium enrichments are lower. Transmutation capabilities as high as 50 % can be observed in active repository utilizing water moderated flux. This increase in transmutation is mainly related to bigger thermal neutron capture cross-section in comparison to fast cross-sections. Thermal transmutation of minor actinides is mainly achieved trough neutron capture reactions leading to new minor actinide with shorter half-lives. The half-lives of these new MA are generally very short in the terms of time scale under consideration for LoFR (few thousand years). For our case the only exception is ^{239}Pu, which in fast and thermal fluxes is transmuted mainly trough fission reaction.

***Table 5**: Transmutation capability of water moderated LoFR at a flux 10^{11} n/cm^{2}s.*

Actinide	Initial mass [g]	m_{LoFR}(2000 yr) [g]	m_D(2000 yr) [g]	TC_{LoFR}(2000 yr)
^{237}Np	10 000	8 336	9 994	1.20
^{239}Pu	10 000	5 980	9 442	1.58
^{241}Am	8 000	305.1	324.4	1.06
^{243}Am	2 000	1 243	1 657	1.33
^{244}Cm	10 000	217.60 (100y)	217.77 (100y)	1.001 (100y)

Even if this 50 % transmutation capability seems big, we still need 20 000 yr or more to reduce the activity of these long-lived MA for three orders of magnitude. This is too slow to make any influence on short term waste management policy, especially if we compare LoFR transmutation to advanced transmutation options in closed advanced fuel cycles including partitioning and transmutation (P&T) technologies. Recent P&T studies showed [4], that it is possible to reduce the radio-toxicity of long-lived minor actinides below radio-toxicity of uranium ore in equilibrium with its daughters in 500 to 1500 yr.

However, the transmutation in LoFR should not be viewed only in human life time frames. If we look on it from the point of deep geological disposal, we may see it as a natural analogue. It could help us to understand better different process related to deep geological repository. One of such process is the presence of neutron flux in the repository and the influence of this neutron flux on decay of long-lived isotopes. This subject was questioned by the deep geological disposal community, but never truly answered. Low neutron flux will always be present in any repository due to spontaneous fission of long-lived actinides and due to (α,n) reactions taking place in spent nuclear fuel. Neutron flux within typical 17×17 PWR fuel element with 3.2 % enrichment and burnup of 33 000 MWd/MTU after 60 years of cooling is in the order of 10^3 n/cm^{2}s. Using our developed model we can see that such flux has a negligible effect on decay of MA in first 10 000 years.

4. CONCLUSIONS

The LoFR is a natural slow burning breeder reactor, with strong resemblance to fossil fission reactors found in Gabon. The concentrations of minor actinides in such a reactor are negligible. We introduced and studied the idea of using such LoFR as a clean natural burner for long-lived minor actinide isotopes. Using burnup and decay calculations we showed, that LoFR could not be used for fast and effective transmutation. Fast LoFR have very limited transmutation capacity and in addition they require high uranium enrichments. Thermal LoFR could be easier to design; however, their capabilities can’t be compared to capabilities of dedicated transmutation installations (e.g. advanced fast reactors). But studies of basic physics processes in low flux reactors can help us understand that fission is a natural process, which happened at least once before in Earth’s history. Public acceptance of deep geological repository could significantly benefit from proper understanding of this natural process.

ACKNOWLEDGMENTS

The authors gratefully acknowledge very constructive, inspiring and interesting discussions with J. Marvin Herndon Ph.D. and with Prof. Walter Seifritz about natural reactors and their relation to geological formations in the Earth's interior, which took place during their visit to the Institute for Transuranium Elements, Karlsruhe, Germany.

REFERENCES

[1] G. A. Cowan, *Scientific American*, vol. 235, 1976, pp. 37.

[2] H. Hidaka, and P. Holliger, Geochemical and neutronic characteristics of the natural fossil fission reactors at Oklo and Bangombe, Gabon, *Geochimica et Cosmochimica Acta*, vol. 62, no. 1, 1998, pp. 89-108.

[3] A. P. Meshik, C. M. Hohenberg, and O. V. Pravdivtseva, Record of Cycling Operation of the Natural Nuclear Reactor in the Oklo, *Physical Review Letters*, vol. 93, num. 18, 2004, pp. 182302.

[4] J. Magill, Nuclides.net, Springer Verlag, 2003.

[5] M. Ravnik, and R. Jeraj, Criticality analyses of regions containing uranium in the earth history, *Kerntechnik*, vol. 70, num. 3, 2005, pp. 146-152.

[6] J. M. Herndon, Substructure of the inner core of the Earth, *Proceedings of the National Academy of Sciences of the United States of America*, vol. 93, num. 2, 1996, pp. 646-648.

[7] D. F. Hollenbach, and J. M. Herndon, Deep-Earth reactor: Nuclear fission, helium, and the geomagnetic field, *Proceedings of the National Academy of Sciences of the United States of America*, vol. 98, num. 20, 2001, pp. 11085-11090.

[8] W. Seifritz, Some Comments on Herndon's Nuclear Georeactor, *Kerntechnik*, vol. 68, num. 4, 2003, pp. 193.

[9] Meshik, A.P. et al. "Record of Cycling Operation of the Natural Nuclear Reactor in the Oklo/Okelobondo Area in Gabon", Phys. Rev. Lett. (93) (2004)

[10] Natural Fossil Fission Reactors, Oklo, Gabon, Many internet references can be found on this subject. American Nuclear Society: www.ans.org/pi/np/oklo/, University of Technology: http://www.oklo.curtin.edu.au/

[11] Croft, ORIGEN, *Nuclear Technology*, vol. 62, 1982, pp. 335.

[12] E. Teller, M. Ishikawa, and L. Wood, Completely Automated Nuclear Reactors for Long-Term Operation, *Proceedings of the Frontiers in Physics Symposium,* Lubbock, Texas, USA,

----

26-28 October 1995, American Physical Society, UCRL-JC-122708, Lawrence Livermore National Laboratory, Livermore, California, USA, 1996.

[13] E. Teller, M. Ishikawa, L. Wood, R. Hyde, and J. Nuckolls, Completely Automated Nuclear Reactors for Long-Term Operation II: Toward a Concept-Level Point-Design of a High-Temperature, Gas-Cooled Central Power Station System, UCRL-JC-122708 Pt2, Lawrence Livermore National Laboratory, Livermore, California, USA, 1997, internet address: http://www-phys.llnl.gov/adv_energy_src/ICENES96.html.

Journal of Energy Technology

JET Volume 1 (2008), p.p. 21 - 30

Issue 1, November 2008

www.fe.uni-mb.si/JET

VIBRATION NONLINEAR ANALYSIS OF DIESEL VALVE GEAR

VIBRACIJSKA NELINEARNA ANALIZA KRMILNEGA SISTEMA V DIESELSKIH MOTORJIH

Jurij Avsec[ℜ], Andrej Predin

University of Maribor
Faculty of Energy Technology

Keywords: diesel engines, machine dynamics, nonlinear vibration

Abstract

This paper describes the nonlinear vibration analysis of a new type of valve gear. In order to estimate the cam wear intensity and to compare the new cam designs with the existing ones the dynamic vibration valve gear analysis was made. The real model of the real valve gear design can be written by means of the partial differential equations, the solution of which is a complex task. We used a vibration system with three degrees of freedom. The differential equations were solved by finite differences method and Runge-Kutta method. With help of our models we are able to analyze the kinematics and dynamic behaviour of nonlinear valve spring. On the basis of presented theory we will find in the future research the conditions for chaotic behaviour of valve gear system.

[ℜ] Corresponding author: Ass. Prof. Jurij Avsec, , Tel.: +386-7-6202217, Fax: +386-2-6202222, Mailing address: Hočevarjev trg 1, 8270 Krško, SLOVENIA

E-mail address: jurij.avsec@uni-mb.si

Povzetek

V dieselskem motorju se pri projektiranju krmilnega sistema srečujemo z velikim številom prepletajočih se problemov. Velike napetosti, ki so se pojavljale, so bile vzrok pretirane obrabe dročnikov na odmični gredi dieselskega motorja. Članek opisuje vibracijsko analizo za nov tip odmikala MULTICAM. Hkrati smo s pomočjo Runge-Kutta metode analizirali tudi vpliv nelinearnosti ventilske vzmeti. S pomočjo novega tipa odmikala smo zmanjšali Hertzove tlake na kontaktu med odmikalom ter dročnikom.

----

1. INTRODUCTION

The main task of the valve gear is the exhaust and inlet valve control. In internal combustion engines the valve gear system has an important influence upon the power output and torque as well as on the exhaust gas emission. The forces required for the control are very high due to high accelerations occurring in the valve gear. Apart from the forces, wear and damage of the valve gear are caused also by the reactive reagents and high temperatures primarily on the exhaust side of the thermally loaded valve gear parts. The valve gear of truck and bus engines has experienced a fast development in the past years. In Otto engines for cars the electro-hydraulic valve gear with variable valve gear design has been established in the series production. It has an advantage over the conventional system primarily at the idling at lower engine loading. In racing car engines, the pneumatic valve gear is used already due to a very fast response and the correspondingly very short valve opening and closing times. In truck and bus diesel engines only conventional valve gear designs are used in the series production. One of the most difficult problems in the internal combustion engines are raised from nonlinear mechanics. The problems of nonlinear mechanics are today solved with the methods of mathematics, where the theory of chaos is one of the most successful theories [1-2].

2. EXISTING VALVE GEAR

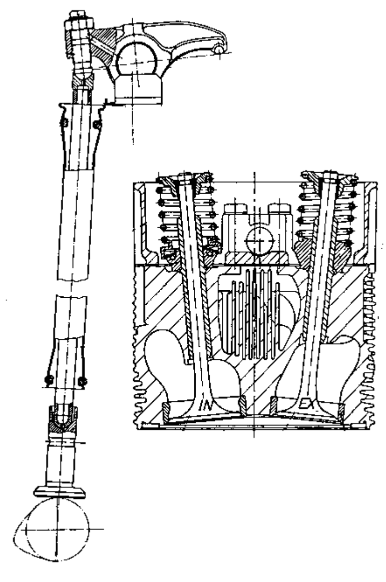

Fig 1: Real valve gear system

In our case, the engine durability test was carried out in TAM BF 6L 515C diesel engine, incorporating a conventional valve gear. After the 3000-hour engine test the manifestations of an intensive wear appeared on the exhaust side of the valve gear. The wear of the exhaust cam

----

was especially intensive right under the top. This type of wear is called the surface wear and it occurs at low peripheral speeds, when the lubrication properties are weakened and high friction occurs between the cam and the follower when the side pressure is high. Both the inlet and exhaust cams in the test engine were designed in accordance with the polysine curve theory [3]. This type of cam is designed so as to yield a continuous acceleration curve.

3. FINITE DIFFERENCES MATHEMATICAL VIBRATIONAL MODEL

In order to estimate the cam wear intensity and to compare the new cam designs with the existing ones, the dynamic valve gear analysis was made. In the references [3] and [4] we have developed the mathematical model for the rigid system and linear vibrational system.

The real valve gear system [5] (shown in Fig. 1) is unsuitable for the formulation of an equation of movement, mainly because it is described by means of partial differential equations. Consequently, the real system is replaced by an equivalent three-mass system (shown in Fig. 2), which may be described through three ordinary second order differential equations. In this reaction, every element of the system is represented by two concentrated masses, connected by a weightless spring, having the stiffness of this element. In addition, rotational movement of a rocker arm is replaced by translatory movement. Portions of masses of two adjacent elements are integrated into a single mass (e.g. a portion of the mass of a push rod and a portion of the mass of a rocker arm form a single mass in the equivalent system), resulting in a system of three concentrated masses, interconnected with springs. Reduced masses and reduced stiffness of the equivalent system are determined on the basis of equality of kinetic and potential energy of the real and equivalent system.

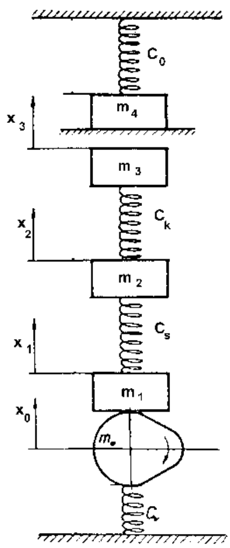

Fig. 2: The mathematical model

The concentrated masses shown in the equivalent system model of the engine valve gear (Fig. 2) are identified in the following way:

- mass m_o represents a mass of a part of the camshaft related to the corresponding valve gear system

$$m_0 = m_{bv} \tag{1}$$

The valve gear equivalent system model (Fig. 2) serves for the formulation of the movement equations of individual masses. The movement of masses m_1 and m_o is defined by the equations:

$$m_1\ddot{x}_1 + m_0 x_0 + c_s(x_1 - x_2) + c_{bv}x_0 = 0 \tag{2}$$

$$x_0 = x_1 - h_p \tag{3}$$

where x_1 is cam follower movement or its actual lift, h_p is cam follower movement, defined by cam profile. The movement of mass m_2 is determined by the equation:

$$m_2\ddot{x}_2 + c_k(x_2 - x_3) + c_s(x_2 - x_1) = 0 \tag{4}$$

At the beginning of the movement, when $h_p < h_z$, the movement equation for mass m_3 has the form:

$$m_3\ddot{x}_3 + c_k(x_3 - x_2) = 0 \tag{5}$$

After the compensation of clearance ($h_p \geq h_z$) mass m_4 is also involved in the movement, opposed by the valve spring force F_0 and the force of gases F_g in the cylinder, acting on the valve:

$$(m_3 + m_4)\ddot{x}_3 + (x_3 - x_2)b_k + (x_3 - x_2)c_k + c_0 x_3 = -F_0 - F_g \tag{6}$$

By rearranging the equations (2) and (3) we obtain:

$$(m_1 + m_0)\ddot{x}_1 + c_s(x_1 - x_2) + c_v x_1 = m_0\ddot{h}_p + c_{bv}h_p \tag{7}$$

In this case, equations (4) and (5) may be written in the form:

$$m_3^*\ddot{x}_3 + c_k(x_3 - x_2) + c_0^* x_3 = F^* \tag{8}$$

for $h_p < h_z$, $m_3^* = m_3$, $c_0^* = 0$, $F^* = 0$ (9)

for $h_p \geq h_z$, $m_3^* = m_3 + m_4$, $c_0^* = c_0$, $F^* = -F_0 - F_g$ (10)

where h_z is valve clearance. Movement x_o represents the movement or deflection of the camshaft to be found in a functional relation, resulting from the cam follower movement, described by means of equation (3): New variables may be introduced into the system of equations (2-9), namely:

z_1=x_1- actual cam follower lift,

----

z_2- cam follower push rod deflection,

z_3- rocker arm deflection

On the basis of equation (10) we can write the next expression:

$$x_1 = z_1,\ x_2 = x_1 - z_2 = z_1 - z_2,\ x_3 = x_2 - x_3 = z_1 - z_2 - z_3 \tag{11}$$

By differentiating the preceding expressions we obtain:

$$\dot{x}_1 = \dot{z}_1,\ \dot{x}_2 = \dot{z}_1 - \dot{z}_2 = \dot{z}_1 - \dot{z}_2,\ \dot{x}_3 = \dot{x}_2 - \dot{x}_3 = \dot{z}_1 - \dot{z}_2 - \dot{z}_3$$

$$\ddot{x}_1 = \ddot{z}_1,\ \ddot{x}_2 = \ddot{z}_1 - \ddot{z}_2 = \ddot{z}_1 - \ddot{z}_2,\ \ddot{x}_3 = \ddot{x}_2 - \ddot{x}_3 = \ddot{z}_1 - \ddot{z}_2 - \ddot{z}_3$$

Introducing these variables into the system of equations (5-10) a final form of differential equations is obtained, describing the movement of the equivalent model of the valve gear system:

$$\begin{bmatrix} m_1 + m_0 & 0 & 0 \\ m_2 & -m_2 & 0 \\ m_3^* & -m_3^* & -m_3^* \end{bmatrix} \begin{Bmatrix} \ddot{z}_1 \\ \ddot{z}_2 \\ \ddot{z}_3 \end{Bmatrix} + \begin{bmatrix} C_{bv} & C_s & 0 \\ 0 & -C_s & C_k \\ C_0^* & -C_0^* & -\left(C_0^* + C_k\right) \end{bmatrix} \begin{Bmatrix} z_1 \\ z_2 \\ z_3 \end{Bmatrix} = \begin{Bmatrix} m_0 \ddot{h}_p + C_{bv} h_p \\ 0 \\ F^* \end{Bmatrix} \tag{12}$$

or in the final form:

$$[M]\{\ddot{z}\} + [K]\{z\} = \{F\}_t \tag{13}$$

$$\{z\}_{t+\Delta t} = [A]^{-1}\left(\{F\}_t - [B]\{z\}_t - [G]\{z\}_{t-\Delta t}\right) \tag{14}$$

$$[A] = \frac{1}{\Delta t^2}[M],\ [B] = [K] - \frac{2}{\Delta t}[C],\ [G] = \frac{1}{\Delta t^2}[M] \tag{15}$$

From this equation the value of the unknown variable z may be obtained in the next moment, if its values are known in two previous moments. This means that for the initial moment the values of the unknown variable z must be known, while subsequently the value of the unknown variable z may be found for an arbitrary moment of time through a predetermined sufficiently small time interval.

4. RUNGE-KUTTA LINEAR MODEL

We can transform Eq. (13) to solve the problem on the basis of Runge-Kutta numerical solution:

$$\dot{z}_1 = z_4, \dot{z}_2 = z_5,\ \dot{z}_3 = z_6 \tag{16}$$

$$\begin{Bmatrix} \dot{z}_4 \\ \dot{z}_5 \\ \dot{z}_6 \end{Bmatrix} = [M]^{-1}\left[\{F\} - [C]\begin{Bmatrix} \dot{z}_1 \\ \dot{z}_2 \\ \dot{z}_3 \end{Bmatrix} - [K]\begin{Bmatrix} z_1 \\ z_2 \\ z_3 \end{Bmatrix}\right] \tag{17}$$

5. RUNGE-KUTTA NONLINEAR MODEL

In the presented paper we have taken into account the nonlinearity of valve spring. The spring force in the model is presented with the next equation:

$$F_{spring} = C_{01}x + C_{02}x^n \tag{18}$$

The first part on the right side shows linear part and the second part presents the nonlinear contribution of n-th order.

$$\dot{z}_1 = z_4, \dot{z}_2 = z_5, \dot{z}_3 = z_6 \tag{19}$$

$$\begin{Bmatrix} \dot{z}_4 \\ \dot{z}_5 \\ \dot{z}_6 \end{Bmatrix} = [M]^{-1}\left[\{F\} - [C]\begin{Bmatrix} \dot{z}_1 \\ \dot{z}_2 \\ \dot{z}_3 \end{Bmatrix} - [K]\begin{Bmatrix} z_1 \\ z_2 \\ z_3 \end{Bmatrix} - \begin{Bmatrix} 0 \\ 0 \\ C_{02}(z_1 - z_2 - z_3)^n \end{Bmatrix}\right] \tag{20}$$

6. RESULTS AND DISCUSSION

On the basis of presented mathematical models we are able to determine and to analyze some very important parameters. By designing and analyzing of the valve gear, we wished to reduce the tensions primarily at the top of cam without having to substantially change of other parameters. Due to the presented problems we have used MULTICAM cam [3], designing by means of seven curves. At the same time we wanted to analyze the influence of valve spring nonlinearity on valve and cam follower lift and to analyze the caused deflections.

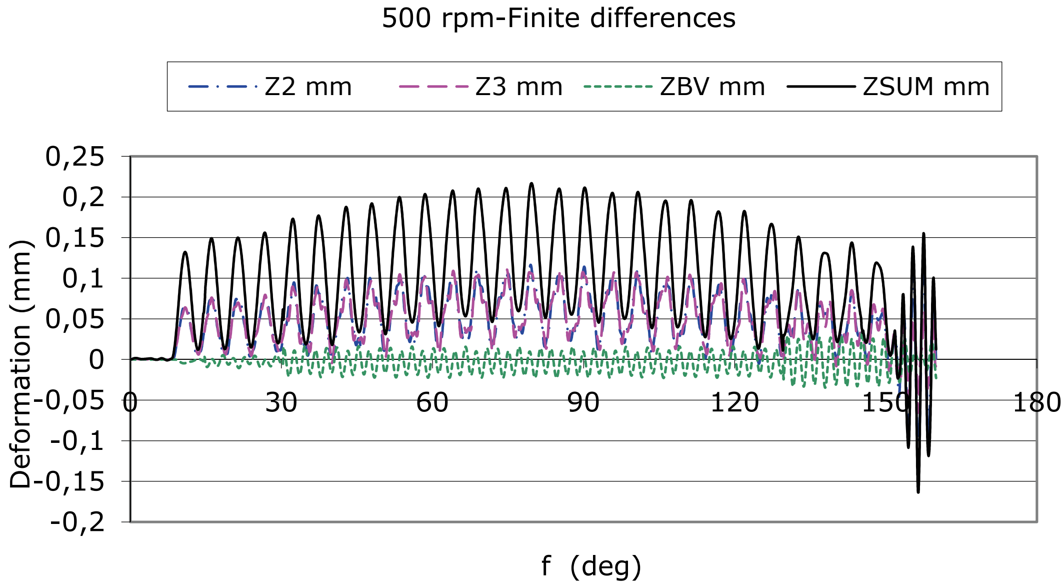

Figure 3: Numerical results obtained with finite differences method

b) Runge Kutta

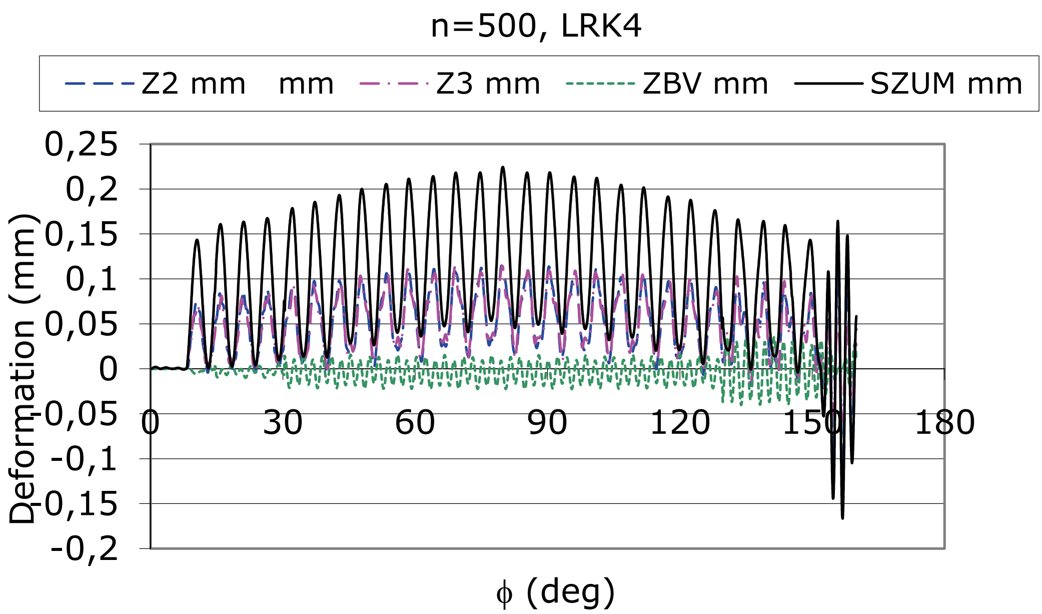

Figure 4: Numerical results obtained with Runge-Kutta method

Fig. 3 shows on the basis of the finite differences method the cam follower push rod deflection (z_2), rocker arm deflection (z_3), the deflection of camshaft (zbv) and the complete deflection of the valve gear system (zsum). Fig. 4 shows the deflections obtained by Runge-Kutta 4 linear

----

method. Figures 5 and 6 show the cam lift (z_1) and the deflections obtained by Runge-Kutta 4 nonlinear model with the fourth order of nonlinearity. Figures (3-6) are obtained at n=500 rpm.

It is evident from Figs. 3-4 that the results obtained with finite differences and Runge-Kutta method agrees well in the amplitude and in the shape of the frequency spectrum. Figs. 5 and 6 show that the linearity has a slight influence on the magnitude of the amplitude and on the shape of frequency spectrum. Figure 7 shows the cam lift of linear spring.

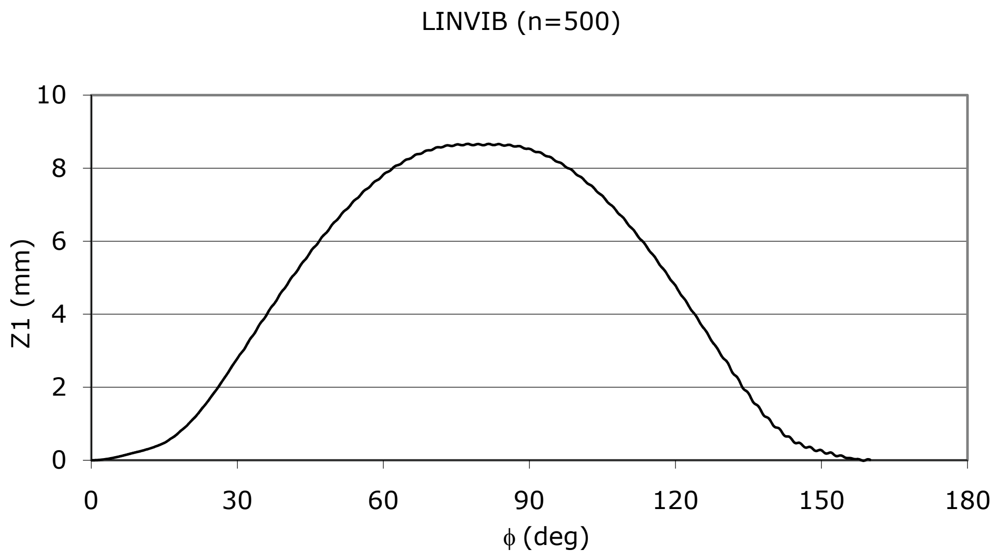

Figure 5: Cam lift in the case of valve spring nonlinearity of fourth order

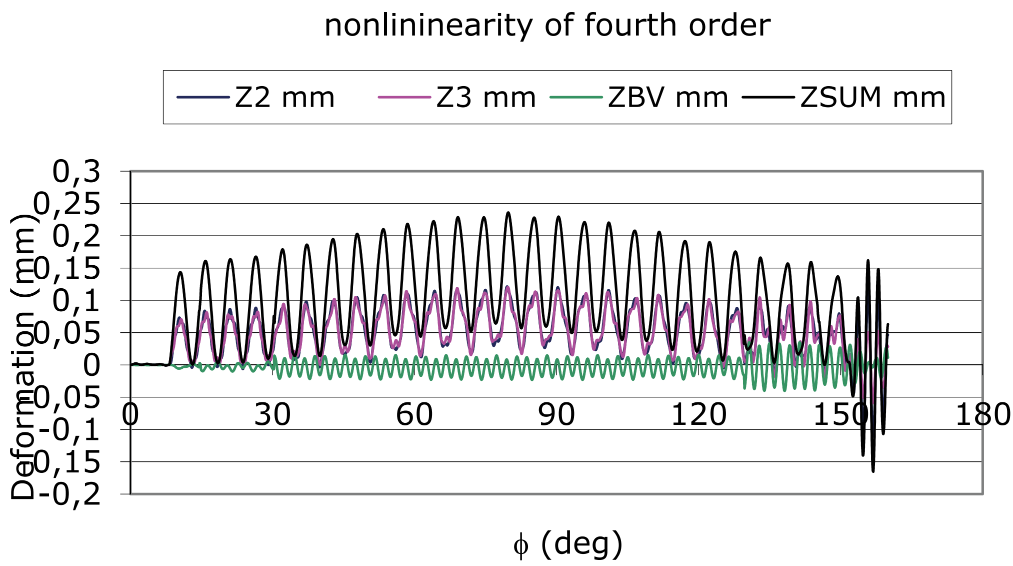

Figure 6: Deformation with nonlinearity of fourth order

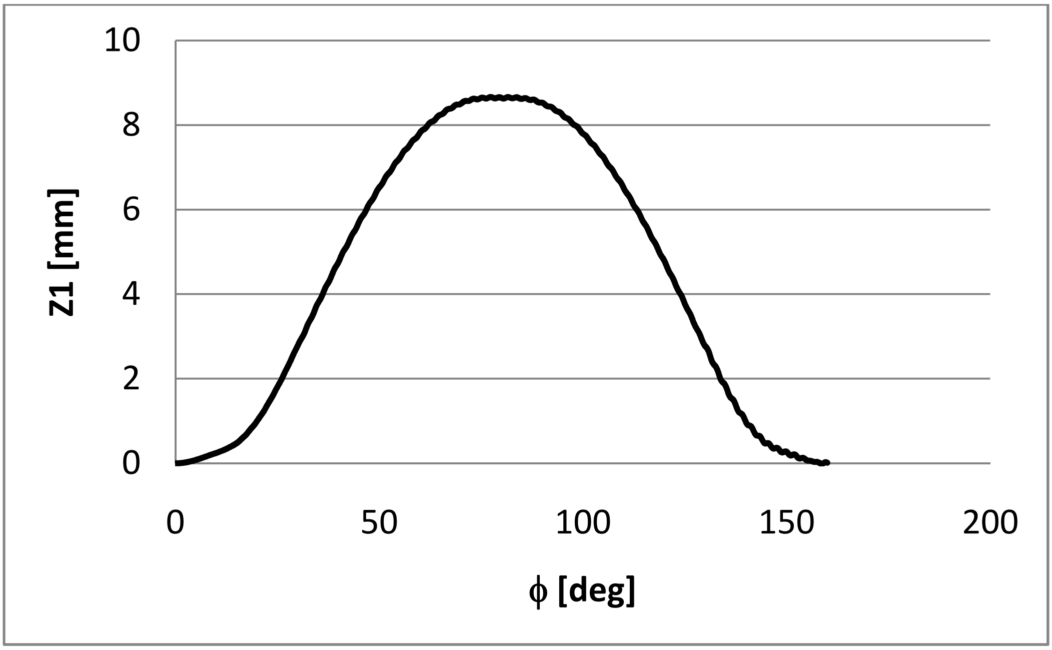

Figure 7: Cam lift in the case of linear valve spring

7. CONCLUSION

The design of diesel engine valve gear is often accompanied by a large number of complex problems, which have to be solved. In our case the problem was the intensive wear at the top of the exhaust cam profile after the 3000-h test on the engine. In the paper are used vibration systems with three degrees of freedom. We have also analyzed the nonlinearity of valve spring with the MULTICAM cam design.

REFERENCES

[1] H. Nayfeh, D.T. Mook, Nonlinear Oscillations. (John Wiley & Sons, Chichester, New York, 1979)

[2] J.M.T. Thompson, H.B. Stewart, Nonlinear Dynamics and Chaos. (John Wiley & Sons, Chichester, New York, 1986).

[3] J. AVSEC, M. MARČIČ, M. OBLAK, Valve Gear Refinement. J. Mech. Des. , Vol. 124, 86-90 (2002).

[4] J. AVSEC, M. OBLAK, "Valve Gear Vibrational Analysis and Development of New Cam Design". V: The International Conference on Computational Methods, December 15-17, 2004, Furama RiverFront, Singapore. Conference digest. [Faculty of engineering, National university of Singapore, cop. 2004].

[5] H. Kanesaka, K. Ahila, H. Sahai, *A New Method of Valve Cam Design* HYSDYNE CAM, SAE 770777.

Journal of Energy Technology

JET Volume 1 (2008), p.p. 31 - 42

Issue 1, November 2008

www.fe.uni-mb.si/JET

EVALUATION OF NEUTRON SCATTERING IN FUSION REACTOR DIAGNOSTICS AND TILE MATERIAL

OCENA SIPANJA NEVTRONOV V DETEKTORSKEM MATERIALU FUZIJSKEGA REAKTORJU TER V PRVI STENI

Igor Lengar [1,2]

[1] Jožef Stefan Institute
Jamova 39, SI-1000 Ljubljana, Slovenia
igor.lengar@ijs.si

[2] Univerza v Mariboru
Fakulteta za energetiko
Hočevarjev trg 1
8270 Krško, Slovenia

Keywords: neutron scattering, neutron diagnostics, fusion reactor

Abstract

The neutron diagnostics systems in fusion reactors, mainly used to measure plasma parameters, are exposed to direct – plasma – neutrons and an indirect component of scattered neutrons. Detectors are usually experimentally calibrated with known neutron sources in order to account for both components. In tokamaks, minor changes in the torus structure are frequently performed, which can influence the scattered neutron contribution to the detector response and possibly deteriorate its calibration. The influence of scattered neutrons can be important in particular for components close to the detector positions.

The positions from which the neutrons are scattered prior to their detection in detector systems and the influence of the first wall material on the neutron backscattering are investigated in the paper. The study is performed for a typical in-vessel diagnostic, located in the upper part of the torus. The tile material influence is performed for the most frequently used materials, namely carbon, beryllium and tungsten. The neutron transport code MCNP was used. The estimation was performed for neutron fluxes in a typical fusion reactor spectrum.

Povzetek

Detektorski sistemi v fuzijskih reaktorjih so izpostavljeni direktnim (plazemskim) ter sipanim nevtronom. Kalibracije detektorjev običajno izvedemo eksperimentalno s točkastim nevtronskim izvorom. V fuzijskih reaktorjih - tokamakih lahko manjše spremembe v notranjosti torusa, vplivajo na sipano komponento in tako na odziv detektorja, kar lahko vpliva na poslabšanje njegove kalibracije. Vpliv sipanih nevtronov bi lahko bil še posebej pomemben ob spremembah komponent v neposredni bližini detektorjev.

V članku je opravljena analiza sipanja nevtroni v detektorje ter vpliva materiala prve stene reaktorja na povratno sipane nevtrone. Analiziran tipičen nevtronski detektor, lociran v zgornjem delu torusa. Študija vpliva materiala prve stene je narejena za najpogosteje uporabljane materiale in sicer ogljik, berilij in volfram. Transport nevtronov je opravljen s program MCNP, ki temelji na osnovi metode Monte Carlo. Uporabljen je tipičen nevtronski fluks, kot ga najdemo v velikih fuzijskih reaktorjih.

----

1. INTRODUCTION

Fusion is one of the promising energy sources for the mid-term future. The plasma parameters in fusion reactors are measured with several diagnostic systems through the neutron and gamma fluxes, emitted from the plasma. The systems do not, however, detect only the direct plasma neutrons but also those, scattered into the detectors from torus structures. The response of the detectors is thus a complicated function and they are experimentally calibrated with point neutron sources, what is usually done only once per several years or in the case of some tokamaks only once – before the start of operation [1]. Some of the diagnostics systems – the profile monitors – are shielded from the plasma with several meters of shielding material and particles reach the detectors through flight tubes, built into the shield [2]. In this way only a localized volume of the plasma (under a narrow angle) is observed. The detector response is in this case weighted with noise due to the neutrons, scattered into the flight tube from the opposite side of the torus.

In large tokamaks, minor changes in the torus structures are performed on frequent basis. It was anticipated, that changes in the torus, close to the detector positions, could be crucial on the detector response. The material of the first wall tiles can be changed as well. In the present work, determination of the positions, from which neutrons are scattered into the detectors and the change in the neutron flux, scattered back from the first wall tiles, due to a change of the tile material, are investigated. The backscattered flux can namely directly contribute to the detector noise, especially in the case of the directionally sensitive profile monitor, and the original experimental calibration could be disturbed. The judgment about extent of both phenomena is performed with Monte Carlo calculations with the MCNP code [3] for the case of a neutron field, as is expected in large tokamaks (JET). The detector position for the estimation of the in-scattering into the detector is chosen in the upper part of the torus which is a typical position in a large tokamaks. The material of the tiles was exchanged between three candidate materials for the first wall of fusion reactors namely carbon, beryllium and tungsten [4]. The estimation is important in particular, because Monte Carlo calculations, frequently used for neutron flux determination, fail in the case of the fusion reactor profile monitors due to the very low neutron flux at the position of the later.

2. SCATTERING OF NEUTRONS INTO THE DETECTOR

The most direct method for measuring plasma parameters is through neutron detection. A neutron probe as found in tokamaks of typical large fusion reactors is presented in Figure 1. The probe is mounted in the upper part of the torus – white in Figure 1 – surrounded by two limiters, used to confine the plasma. It is usually not possible to avoid the presence of a large number of scattered neutrons in addition to the desired direct ones. In the case of the described probe the straight forward question is whether the response of the probe could be improved if the two closest limiters were removed.

To answering this question, a new technique for tracking of individual neutrons on their path from the plasma to the detectors, was developed. The technique is based on the Monte Carlo neutron transport code MCNP and made it possible to examine the positions, from which neutrons are scattered into the detectors. The emphasis was given on the amount of neutrons, scattered from the closest limiters.

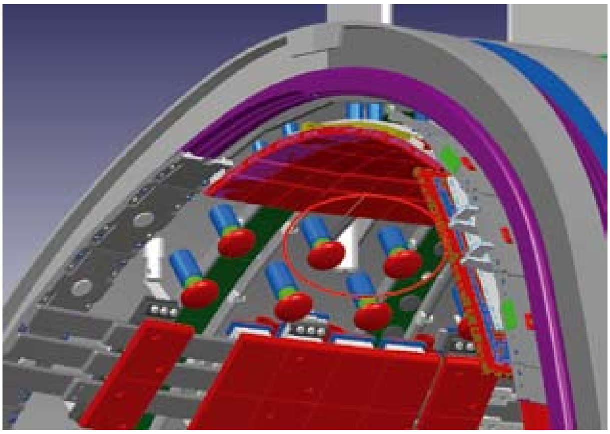

Figure 1: *The position of the neutron probe (in white color) in the upper part of the torus and two mushroom limiters in the immediate proximity. The case of the tokamak of a typical large fusion reactor.*

The results were astonishing, showing that approximately only every seventh detected neutron originates directly from the plasma, the rest are scattered neutrons. This number can be improved by using a lower neutron detection energy cut-off, but this does not significantly affects the ratio of neutrons, scattered into the probe form the closet limiters. This ratio is always around 15%. The exact ratios, for three cases of different cut-off energies, are presented in Table 1.

Table 1: *The percentage of the neurons, scattered from the closest two limiters into the neutron probe.*

Lower energy cut-off	**None**	**100 keV**	**1.5 MeV**
Ratio of neutrons Scattered from limiters [%]	**13**	**13**	**15**

It is observed, that the ratio of all neutrons, scattered into the detectors from the closet limiters is considerable. It however turned out, that their absence does not significantly changes the detector response, this change is less than 2%. If the limiters are namely removed, the neutrons scatter into the detectors from other structures.

It has been determined, with an analysis of the neutron paths that a typical neutron scatters for more than 200 times prior to its detection. The neutron track covers a large portion of the torus during this process, making it in principle possible to influence the detector response even by removing or adding structures in a distant part of the torus. A path of a typical neutron is presented in Figure 2.

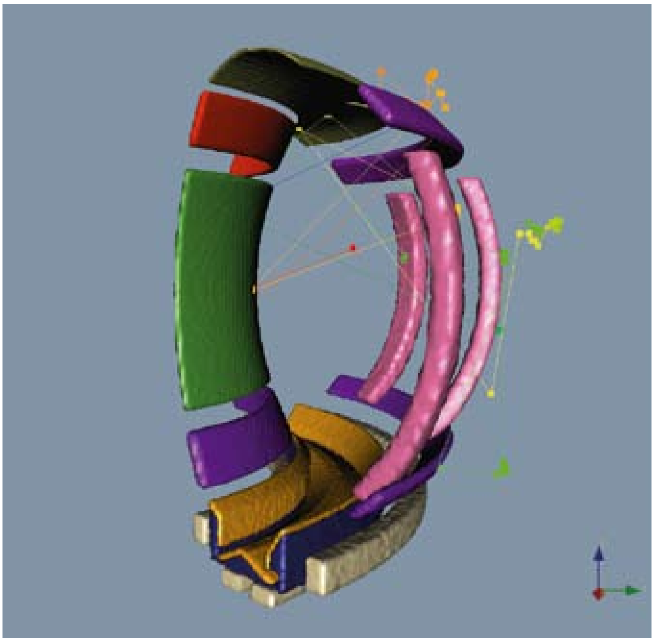

Figure 2: *The path of a neutron from its origin in the plasma to its detection (only some of the in-vessel structures are presented in the figure).*

The main outcome of this part of the work was thus, that changing of any structure, even close to the detector, does in general not significantly influences the response of the detector.

3. BACKSCATTERING IN CARBON, BERILLIUM AND TUNGSTEN

All backscattering calculations have been performed in a simplified 1D geometry for the tile material with a thickness of 2.5 cm. The tile was mounted onto a structural plate of the same thickness made from inconel. Both plates in contact (combined thickness of 5 cm) were large in the other two dimensions. This configuration resembles the true situation in e.g. the JET tokamak [5], where the tiles are presently made of graphite. At some distance behind the tiles two other layers of material – representing the vessel and coils – were modelled in order to mimic the real situation in a fusion reactor. The necessary input for the calculations is the angular dependent neutron spectrum at the position of the plasma facing surface of the tile. As a representative spectrum, the one, encountered at the saddle tile (located vertically above the position of the plasma) of the JET tokamak [6], was chosen and is presented in Figure 3. Similar spectra are expected to exist in other large tokamaks employing a DD plasma.

The transport calculations of the neutrons in the tiles and the supporting structures have been performed with the MCNP code. As explained earlier, the likely neutron spectrum on the first wall was used as the input flux, entering the tile. The angular-energy distribution of the backscattered flux on the same surface (the plasma facing surface), i.e. exiting the tile, was then studied.

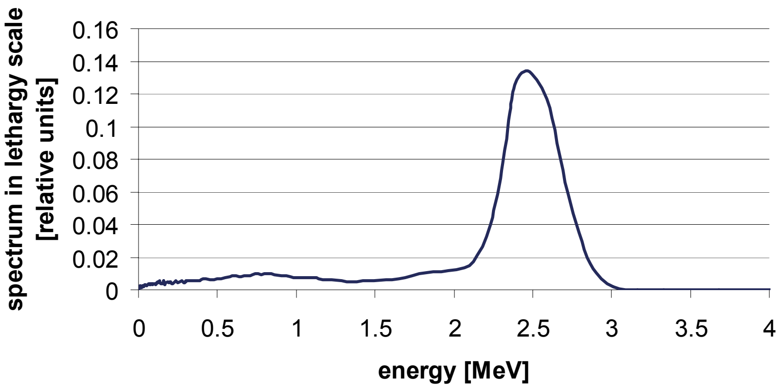

Figure 3: The total neutron spectrum, used as the input for the transport calculations. This spectrum is encountered at the saddle tile of the JET tokamak [2], in the DD plasma case.

The results were tallied for different angle and energy distributions. The angle bins were 0, 0.1, 0.2, ..., 0.9, 1 in the cosine of the angle, denoted as η (i.e. $\eta=\cos(\varphi)$, φ is the angle with respect to the normal to the surface). In this case 1 means the direction of the surface normal and 0 means parallel with the surface. The standard VitaminJ structure was chosen for the energy bins. The calculated angular dependent flux for the three different tile materials (C, Be and W) is presented in Figures 4 to 6.

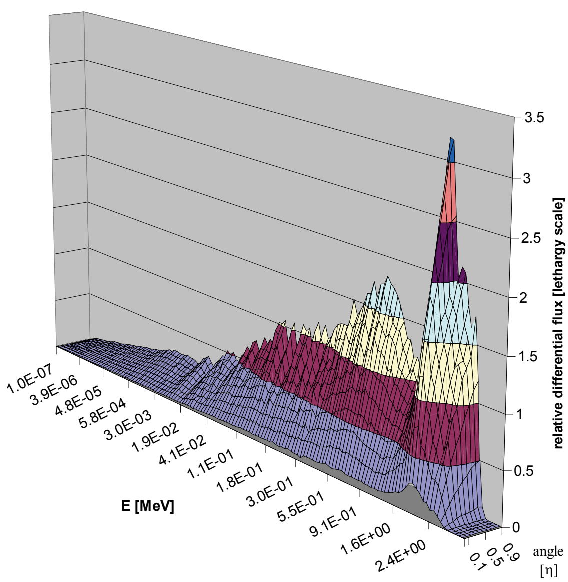

Figure 4: The angular-energy distribution of the backscattered flux, the tile material is carbon (2.5 cm thickness), mounted on 2.5 cm of inconel.

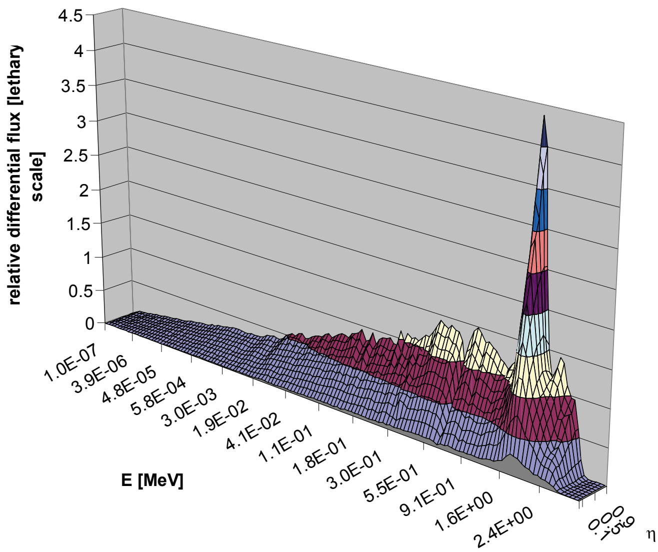

Figure 5: The angular-energy distribution of the backscattered flux, tile material beryllium.

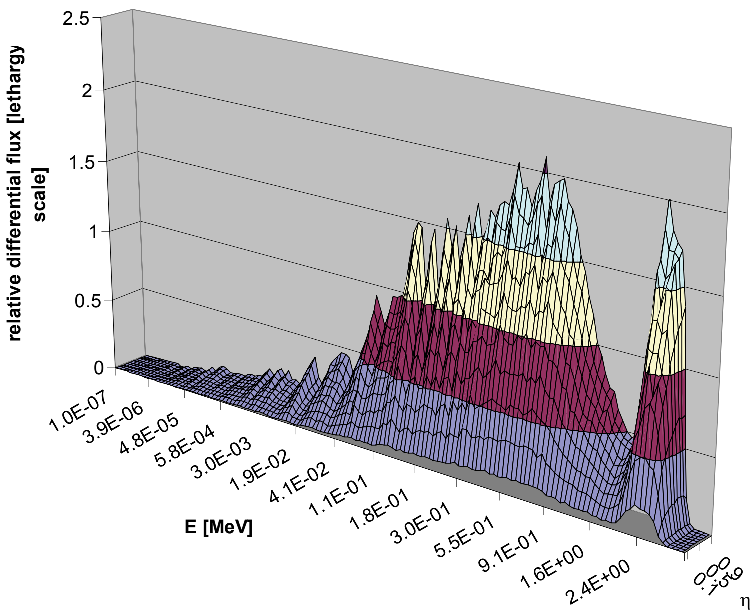

Figure 6: The angular-energy distribution of the backscattered flux, tile material tungsten

----

More illustrative than the absolute value of the fluxes is the difference of the backscattered flux between the individual cases. This difference may namely influence the detector response. In Figure 56the relative difference is presented arising from a possible change of the tile material from carbon to beryllium, i.e. the relative (with respect to the smaller of both values) difference of the data, presented in figures 3 and 2.

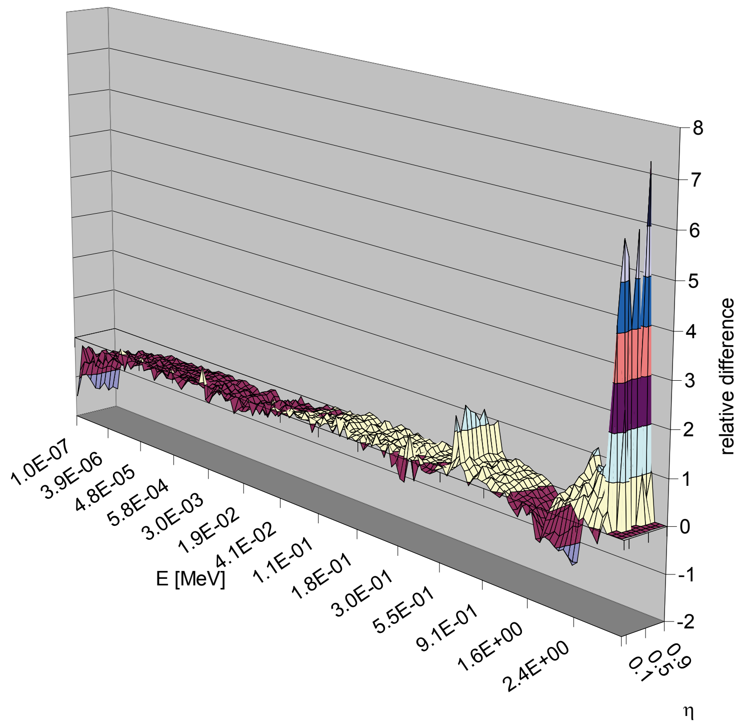

Figure 7 Relative differences, with respect to the smaller of both values, in the angular-energy distribution between the cases of carbon and beryllium tile material.

It can be observed from Figure 7 that the difference in the backscattered neutron flux in some parts of the energy – angle distribution, is quite large. The largest difference is observed around the DD plasma neutron energy of 2.5 MeV, At energies lower than cca. 0.5 MeV, the difference is, however, small.

3.1 Angular distribution of backscattered neutrons

It can be observed from Figures 4 - 6, that in this (lethargy) presentation the backstattered flux is highly energy dependent. Especially interesting is the depression of the flux in the case of Be at the energy around 0.6 MeV, which can be attributed to the increased cross-section of beryllium for neutrons at this energy. The angular dependence at a particular energy is, however, in the entire energy range monotonically increasing from the value of η = 0 to η = -1. This trend is observed for all three materials. Figure 8 represents the angular dependence of the

----

backscattered flux in the η representation for the energies of 10 keV and 1.5 MeV for the three materials.

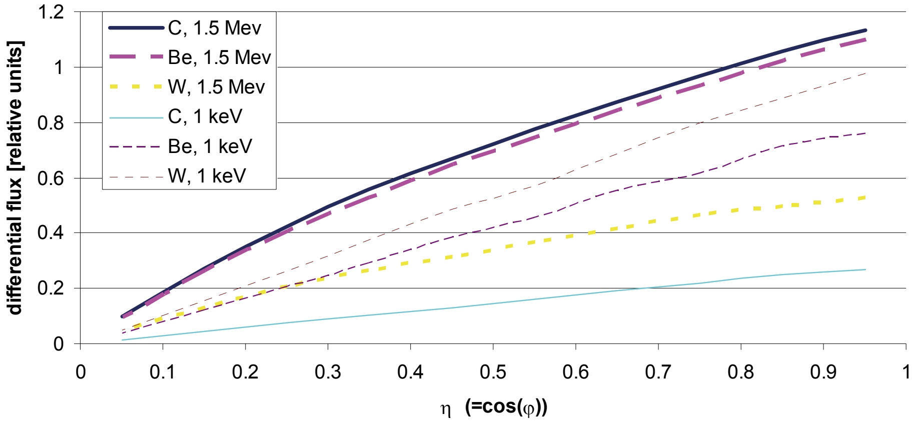

Figure 8: Angular distribution of the backscattered flux at the energies of 1 keV and 1.5 MeV for the C, Be and W tiles.

As can be seen, the distribution is forward peaked, the forward directions being thus more likely than those, under a larger angle with respect to the normal. This behaviour is observed for all materials at both energies.

3.2 Influence of the tile change on detector response

As already noted, Figure 7 reveals that although the thickness of the exchanged tile material is only 2.5 cm, significant difference in the backscattering in some energy – angle tallies can be observed. The exact influence of this difference on the response of a detector is complicated to compute and has to be made by employing transport calculations. A simple judgment about the extent of the phenomenon can, however, be made on the basis of the overall ratio of the scattered neutrons with respect to the direct ones in the neutron flux at the detectors. It has already been noted that the detector response is composed from the flux of neutrons, coming directly from the plasma (and are not affected by tile material change) and from the back-scattered neutrons. The observed difference in the back-scattered flux has, thus, to be multiplied with the overall importance of these neutrons.

The correct value is again difficult to obtain for in-vessel diagnostic systems, since they are exposed to neutrons, which are on average scattered many times prior to reaching the detectors [1]. A simpler comparison between the direct and scattered flux can be made for the directionally very narrowly oriented profile monitors. Their response is, to a large extent, composed from direct – plasma – neutrons and from neutrons, scattered form the opposite side of the torus into the flight tubes of the profile monitors.

It has been argued, that the ratio of the scattered to the direct neutrons in a profile monitor is satisfactory represented by the ratio of the neutrons, impinging on the tile surface (the spectrum is represented in Figure 3), to the backscattered neutrons (Figures 4 to 6). In order to derive this ratio the fact, that the detectors are sensitive only to neutrons above some threshold energy, has been used. This lower energy has been set to 1 MeV (only the case of DD plasma neutrons is investigated in the paper).

The derived ratio between the backscattered and the impinging neutrons at the location of the tile has been found to be roughly one third above the threshold energy of 1MeV.

After having an estimate about the ratio of the backscattered neutrons with respect to the impinging ones, the influence of the change in the detector response due to the change in the backscattered neutrons as the result of tile material change can be estimated. For any relevant estimates for a particular case, the desired energy-angular distribution, calculated in section 3, should be implied. At this stage only a crude estimate of the possible change due to the tile change is performed. For this reason another similar step is performed, namely the relative difference in the backscattered neutrons above the threshold energy of 1MeV is investigated. It turns out, that this difference amounts to up-to 50 percent in the backscattered flux between all three materials investigated.

In this way, we can make estimation about the influence of the exchange of the tile material on the overall response of the profile monitors. This influence is possibly in the range of some 10 percent or even slightly above this value.

It should be noted, that the above derivation reflects only an estimation of the tile material change on the response of profile monitors in fusion reactors. The true value should be derived on an exact knowledge of parameters of individual reactors. It is however extremely difficult to calculate the exact values with Monte Carlo calculations, due to the very low flux in the region of the profile monitor detectors. Such estimations, like the one performed in this paper, are thus essential part of a tokamak upgrade planning.

4. CONCLUSIONS

The influences of the neutron in-scattering effect from torus structures into the detectors and the change of the first wall material in a tokamak on the neutron backscattering were investigated. The presence of structures close to the neutron detectors or the effects of the change in backscattering characteristics can possibly influence the response of the tokamak detector systems. It has been found, that neutron scattering paths are complex and that structures in the immediate vicinity of neutron diagnostics in general do not significantly affect their response.

The study of the backscattering was performed for the most frequently used tile materials, namely carbon, beryllium and tungsten by using the neutron transport code MCNP. It was found, that the relative difference in the backscattered neutron flux, in some of the angle-energy tallies, amounts up-to a factor of ten. The average difference above the threshold energy of 1 MeV is however smaller; the backscattered fluxes for all three materials differ from each other by less than a factor of two. An estimate of the possible influence on the profile monitor response was performed on the basis of the fact that the backscattered flux amounts to one third of the impinging neutron flux. The influence has been found to be possibly in the range of some 10 percent of the overall detector response.

REFERENCES

[1] A. Murari et al., “Measuring the radiation field and radiation hard detectors at JET:next term Recent developments”, Nucl. Instr. Meth. A, 593, 3, (2008), pp. 492-504.

[2] O. N. Jarvis, J. M. Adams, F. B. Marcus and G. J. Sadler, “Neutron profilenext term measurements in the Joint European Torus”, Fusion Eng. Des. 34-35, 1997, pp. 59-66.

[3] ORLN, MCNP – A General Monte Carlo N-Particle Transport Code, Los Alamos National Laboratory, Los Alamos, 2003.

[4] F. Druyts, J. Fays and C. H. Wu, “Interaction of plasma-facing materials with air and steam”, Fusion Eng. Des. 63-64, (2002), pp. 319-325.

[5] M. A. Pick, “The technological achievements and experience at JET”, Fusion Eng. Des. 46, 2-4 (1999) pp. 291-298.

Journal of Energy Technology

JET Volume 1 (2008), p.p. 43 - 58

Issue 1, November 2008

www.fe.uni-mb.si/JET

FUZZY APPROACH IN PROCESS OF MULTIPLE-ATTRIBUTE DECISION MAKING

MEHKI PRISTOP V PROCESU ODLOČANJA PO VEČ LASTNOSTIH

Janez Usenik$^{\Re}$

Keywords: *decision, alternative, criterion, fuzzy logic, fuzzy numbers, rank*

Abstract

In the decision making problems the decision maker makes a choice based on how each possible action affected a single variable or attribute. But in many real situations the action chosen depends on how each possible action affects more than one attribute. Such problems of the decision making with multiple objectives are called multiattribute (or multiple-attribute) decision making. In general in decision methods we assume that values are crisp numbers. However, most of the real multiattribute decision-making problems contain mixture of fuzzy and crisp data. In some cases several of the values that certain alternatives take by particular criteria are not given quantitatively but represent fuzzy numbers. The method for solving fuzzy multiattribute decision-making problems consists of two steps. In the first step, the linguistic terms are transformed into crisp scores. In the second step, any of the classical multiattribute decision-making methods for obtaining the final rank of the considered alternatives can be applied. In this article is given a decision-making problem for multiple attributes; at the end we have a numerical example.

$^{\Re}$ Corresponding author: prof. ddr. Janez Usenik, Tel.: +386 40 647 689, Mailing address: Faculty of Energy Technology, University of Maribor, Hočevarjev trg 1, 8270 Krško, Slovenija, E-mail address: janez.usenik@uni-mb.si

----

Povzetek

V postopku odločanja odločevalec izbere odločitev glede na posledice, ki jo ima vsaka od posameznih možnih alternativ. V večini konkretnih primerov je izbor odvisen ne le od ene, pač pa od več posledic - v takšnih primerih govorimo o odločanju po več lastnostih. Standardne metode odločanja predpostavljajo, da so posledice alternativ podane kot natančno eksplicitno določeni numerični podatki. V dejanskih situacijah pa pri problemih odločanja po več lastnostih prihaja tudi do podatkov, ki so le opisni oziroma mehki. Metoda reševanja takšnih problemov pri sprejemanju odločitev po več lastnostih z uporabo mehke logike sestoji iz dveh korakov. V prvem koraku je potrebno lingvistične pojme na osnovi pravil mehke logike pretvoriti v natanko določene številčne podatke, v drugem koraku pa na tako pridobljenih podatkih uporabiti eno od znanih kvantitativnih metod v postopku sprejemanja odločitev. V članku je prikazan takšen mehki odločitveni model za odločanje po več lastnostih, dodan je še numerični primer.

----

1. INTRODUCTION

All we have to make various decisions in our professional work as well as in our private life and making decisions is a part of our daily life. For example, we have to decide where should we eat, should we drive to work by train or by car, should we buy or rent a car, should we have a dog and so on. Most of these decions are actually not very important, and are made using a combination of experience, intuition and subjectivity. But in professional work decisions are very important and decision makers are very hard work and they need a more formal approach to decision-making. The decisions that planners have to make are for example choosing optimal stocks according to the demand and the capacities of the production, choosing an optimal project schedule, choosing the best location for a new power plant, choosing the best performer for inner transport in the plant etc. Generally, we must to pick up one alternative from a set of possible alternatives or to rank all these alternatives. The ranking of the alternatives is ever done according to a lot of number of criteria that are mutually conflicting. Suppose a company makes a product but finds its profit is too low. What to do? To reduce costs or incrise the price. But if the price is increased the demand may go down. On the other hand, if costs are reduced the price may be reduced and demand may go up. If demand changes, the facory may have to reschedule production and change marketing strategies. Chanded production schedules could affect production of other items, change employment prospect and so on. But in any situation where a decision is needed we can find (Waters, 1997): a) a decision maker is always responsible for making decisions, b) a number of alternatives are available to the decison maker, who must choose one of them, c) the object of the decision maker is to choose the best alternative, d) when the decision has been made, events occur over which the decisin maker has no control, e) each combination of an alternative chosen followed by an event happening leads to an outcome that has some measurable value.

In the decision making problems the decision maker makes a choice based on how each possible action affected a single variable or attribute. However, in many situations the action chosen depends on how each possible action affects more than one attribute. Such problems of the decision making with multiple objectives are called multiattribute decision making. To solve these problems a lot of different methods have been developed, belonging to the field multiple attribute decision making. The problem in making decisions under uncertanty is that the informantions we have about some variables are tipically vague, amgiuos and otherwise fuzzy. The decision maker has to make his decisions within a fuzzy enviroment (Ross, 2007), (Teodorović, Vukadinović, 1998), (Zimmermann, 2001). A lot a methods was developed, in our article we are using basis Chen and Hwang algorithm (Chen, Hwang, 1992), but which is improved with some corrections.

2. THE MATHEMATICAL MODEL OF THE MULTIPLE-ATTRIBUTE DECISION MAKING

We have *m* alternatives $A_1, A_2, \ldots, A_m$ and *n* attributes (objectives) $X_1, X_2, \ldots, X_n$ given in advance. Values x_{ij} are given that certain alternatives A_i, $i = 1, 2, \ldots, m$ take by particular attributes (criteria) X_j, $j = 1, 2, \ldots, n$. In Table 1 the scheme of decision problem is shown.

By *m* we denote the total number of alternatives, and by *n* the total number of attributes according to which the considered alternatives are compared.

***Table 1:** Values x_{ij} in the scheme of decision*

Attribute Alternatives	X_1	X_2	•	•	X_n
A_1	x_{11}	x_{12}	•	•	x_{1n}
A_2	x_{21}	x_{22}	•	•	x_{2n}
•	•	•	•	•	•
•	•	•	•	•	•
A_m	x_{m1}	x_{m2}			x_{mn}

All values from table are given in decision matrix *D*:

$$D=\begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} = \left[x_{ij} \right]_{m\times n} \tag{2.1}$$

For solving the multiattribute decision making problems various methods for ranking the alternatives have been developed. The classical methods are: the dominance method (dominated actions), the maximin criterion, the maximax criterion, the minimax regret method, the expected value criterion, Pareto optimality criterion, the distance from target method, the analytic hierarchy process (AHP) and so on.

In this work we will use the AHP method (Winston, 1994) as follows.

Suppose there are *n* objectives. We begin by writing down a $n\times n$ matrix *A*, known as the pairwise comparison matrix. The entry in row *i* and column *j* of *A* (the element a_{ij}) indicates how much more important objective *i* is than objective *j*. Importance is to be measured on an integer valued 1-9 scale (Table2). For all *i* it is obviously that $a_{ii}=1$. If $a_{ij}=k$, $k>1$, objective *i* is *k*-times more important than objective *j*. Thus, it is necessary that $a_{ji}=k^{-1}$.

Table 2: Interpretation of entries in a pairwise comparison matrix

Value of a_{ij}	Interpretation
1	Objectives *i* and *j* are of equal importance
3	Objectives *i* is weakly more important than objective *j*
5	Experience and judgement indicate that obj. *i* is

----

	strongly more important than objective *j*
7	Objectives *i* is very strongly more important than objective *j*
9	Objectives *i* is absolutely more important than objective *j*
2,4,6,8	Intermediate values, for example a value of 2 means that objective *i* is between equal importance and more important then objective *j*

Let w_i is the weight given to objective *i*. To describe how the AHP determines the w_i, suppose that the decision maker is perfectly consistent. Then her pairwise comparison matrix should be of the following form:

$$A = \begin{bmatrix} \frac{w_1}{w_1} & \frac{w_1}{w_2} & \cdots & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & \frac{w_2}{w_2} & \cdots & \frac{w_2}{w_n} \\ \vdots & \vdots & & \vdots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \cdots & \frac{w_{n1}}{w_n} \end{bmatrix} \tag{2.2}$$

Now suppose that a consistent decision maker has a pairwise comparison matrix *A* of the form (2.2). Now we wish recover the vector $\vec{w} = \begin{bmatrix} w_1 & w_2 & \cdots & w_n \end{bmatrix}$ from matrix A. Consider the system of *n* equations $A\vec{w}^T = b\vec{w}^T$, where *b* is an unknown number and $\vec{w}^T$, is an unknown *n*-dimensional column vector. For any number *b* this equation always has the trivial solution. If *A* is the pairwise comparison matrix of a perfectly consistent decision maker and we do not allow $b = 0$, then we have only the non-trivial solution $b = n$ and vector $\vec{w} = \begin{bmatrix} w_1 & w_2 & \cdots & w_n \end{bmatrix}$. This shows that for a consistent decision maker, the weights w_i can be obtained from the only nontrivial solution of equation $A\vec{w}^T = b\vec{w}^T$. However, the decision maker could be not perfectly consistent. Let $b_{\max}$ be the largest number for which equation $A\vec{w}^T = b\vec{w}^T$ has a nontrivial solution $\vec{w}_{\max}$. If the decision maker's comparisons do not deviate very much from perfect consistency, we would expect $b_{\max}$ to be close to number *n* and $\vec{w}_{\max}$ to be close to vector $\vec{w}$. We can now approximate vector $\vec{w}$ by $\vec{w}_{\max}$. It is necessary measuring the decision maker's consistency by looking how close $\vec{w}_{\max}$ is to *n*. To approximate $\vec{w}_{\max}$, we use the two-step procedure: In step 1 we divide each entry in column *i* of *A* by the sum of the entries in column *i*. This yields a new normalized matrix A_{NORM}. In step 2 we have to find an approximation to $\vec{w}_{\max}$ which will be used for our estimate of $\vec{w}$; we

----

estimate every w_i as the average of the entries in row *i* of the matrix A_{NORM}. We must now check the consistency of our decision comparisons. This procedure consists from four steps. In the first step we have to compute $A\vec{w}^T$. In step 2 we compute the number $N = \frac{1}{n}\sum_{i=1}^{n} \frac{i\,\text{th entry in matrix } A\vec{w}^T}{i\,\text{th entry in vector } \vec{w}^T}$. In the step 3 we compute the consistency index *CI* as follows $CI = \frac{\mathrm{N} - n}{n-1}$ and in step 4 we compare *CI* to the random index *RI* for the appropriate value of *n,* given in Table 3 (Winston, 1994).

Table 3: Values of random index *RI*

n	*RI*
2	0
3	0,58
4	0,90
5	1,12
6	1,24
7	1,32
8	1,41
9	1,45
10	1,51

If coefficient *CI* is small, the decision maker's comparisons are probably consistent enough to give useful estimates for the weights. If $\frac{CI}{RI} < 0{,}10$, the degree of consistency is satisfactory. If $\frac{CI}{RI} > 0{,}10$, the degree of consistency is not satisfactory and inconsistencies may exist.

We have now known weights for all the objectives, so on this basis we have to rank the alternatives. The method used in the continuation is based on the simultaneous measurements of the distance of a particular alternative from the "ideal" and "negative ideal" solution (Chen, Hwang, 1992), (Teodorović, Vukadinović, 1998). From the known decision matrix *D* the normalized decision matrix *R* is calculated first:

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} \tag{2.3}$$

Normalized values r_{ij} in (2.3) are calculated as

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}; \quad i = 1, 2, \ldots, m \;; \quad j = 1, 2, \ldots, n \tag{2.4}$$

In the next step, each column's elements in matrix *R* are multiplied by weight w_j, corresponding to a particular column. In this manner, matrix *V* is obtained:

$$V = \begin{bmatrix} w_1 r_{11} & w_2 r_{12} & \cdots & w_n r_{1n} \\ w_1 r_{21} & w_2 r_{22} & \cdots & w_n r_{2n} \\ \vdots & \vdots & & \vdots \\ w_1 r_{m1} & w_2 r_{m2} & \cdots & w_n r_{mn} \end{bmatrix} \tag{2.5}$$

On calculating the elements of matrix *V*, the ideal solution A^* and the negative ideal solution A^- are determined. If all of the criteria are minimum criteria, these solutions are defined as

$$A^* = \left\{ \left(\min v_{ij} \middle| j \in J \right) \middle| i = 1, 2, \ldots, m \right\} = \left\{ v_1^*, v_2^*, \ldots, v_n^* \right\} \tag{2.6}$$

$$A^- = \left\{ \left(\max v_{ij} \middle| j \in J \right) \middle| i = 1, 2, \ldots, m \right\} = \left\{ v_1^-, v_2^-, \ldots, v_n^- \right\} \tag{2.7}$$

where

$$J = \left\{ j = 1, 2, \ldots, n \middle| j \text{ belongs to the min criteria} \right\}$$

When the minimum criteria are concerned, an alternative is better if by these criteria it takes lower values. “Distance” S_i^* of each alternative from the ideal alternative is

$$S_i^* = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^* \right)^2} = \sqrt{\left(v_{i1} - v_1^* \right)^2 + \left(v_{i2} - v_2^* \right)^2 + \cdots + \left(v_{in} - v_n^* \right)^2} \tag{2.8}$$

$$i = 1, 2, \ldots, m$$

“Distance” S_i^- of each alternative from the negative ideal solution is

$$S_i^- = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^- \right)^2} = \sqrt{\left(v_{i1} - v_1^- \right)^2 + \left(v_{i2} - v_2^- \right)^2 + \cdots + \left(v_{in} - v_n^- \right)^2} \tag{2.9}$$

$$i = 1, 2, \ldots, m$$

Relative closeness C_i^* of the alternative A_i to the ideal solution A^* is as follows:

$$C_i^* = \frac{S_i^-}{S_i^* + S_i^-}, \quad C_i^* \in [0,1], \ i = 1, 2, \ldots, m \tag{2.10}$$

Since $C_i^* = 1$ if the alternative $A_i = A^*$ and $C_i^* = 0$ if $A_i = A^-$, the alternative A_i is better if C_i^* is closer to 1. From the set of alternatives $A_1, A_2, \ldots, A_m$ the best alternative is A_i with the largest value of C_i^*.

3. FUZZY APPROACH TO THE MULTIPLE ATTRIBUTE DECISION MAKING

In each of classical methods it is assumed that values x_{ij} in decision matrix *D* are crisp numbers. However, most of the real decision making problems contain some fuzzy data, thus in these cases the decision matrix *D* consists a mixture of fuzzy and crisp data. In these problems all the values x_{ij} are not given quantitatively, but some of them in terms of appropriate linguistic expressions and terms. For example, in the process of the ranking the different engins some of criteria can be numerical variables (price, number of kW, fuel consumption, acceleration, …), while some of the criteria may be linguistic variables, likee comfort (it can be: very comfortable, comfortable, not comfortable and so on), safety (it can be: very safety, safety, not safety, dangerous, …) and so on (Usenik, 2003), (Usenik, Bogataj, 2005), (Zimmermann, 1999). The values of some variables are words or sentences, so also certain values of x_{ij} are words: high, very nice, not safety. This means that In the decision matrix *D* we have crisp and also fuzzy data i.e. crisp and fuzzy numbers.

Because we have crisp and fuzzy numbers in matrix *D* we have to modify the classical multiattribute decision making methods. In this article we use the Chen and Hwang method for solving fuzzy multiattribute decision making problems (Chen, Hwang, 1992). Advantage of this method is simplicity and efficiency. It consists of two steps: a) in the first step the linguistic terms are transformed into crisp numbers and so all the data in matrix *D* are crisp numbers, b) in the second step one of the classical multiattribute decision making methods for obtaining the final rank of the considered alternatives can be applied.

In fuzzy logic the different values for a given linguistic variable represent concepts, not numbers. For example, linguistic values or terms associated with a linguistic variable »efficiency« can be bad, medium, good, very good. Each linguistic term is represented by a specific fuzzy sets: A, B, C and so on. A technical quantity like velocity is measured as a crisp value, like 50 km/h etc. The degree to which the crisp value belongs to a set is represented by a value between 0 and 1. Fuzzy sets are always functions, which map a universe of objects onto the unit interval $[0,1]$. This value is called the degree of membership. The degree of membership in a fuzzy set *A* becomes the degree of truth or a statement and is expressed by continuous function - membership function $\mu_A(x)$. A fuzzy set is an extension of a classical set. If X is the universe of discourse and its elements are denoted by *x*, then a fuzzy set *A* over the set *X* is defined as a set of ordered pairs: $A = \{x, \mu_A(x) | x \in X\}$. Here $\mu_A(x)$ is the grade

----

of membership of element x in set A. The membership function maps each element of X to a membership value between 0 and 1. The greater $\mu_A(x)$, the greater is the truth of the statement that element *x* belongs to set *A*. If A is a convex single-point normal fuzzy set defined on the real line, then A is often termed a fuzzy number (Ross, 2007), (Bogataj, Usenik, 2005). By means of conversion scales certain linguistic terms are easily converted into fuzzy numbers (process of the fuzzification). In the next step, fuzzy numbers must be converted into crisp numbers (process of the defuzzification), (Ruspini, Bonissone, Pedrycz, 1998). A crisp score of a fuzzy number can be obtained by means of the so-called maximizing and minimizing (fuzzy) sets (Teodorović, Vukadinovič, 1998), (Chen, Hwang, 1992). The membership functions of these sets are defined in the form (3.1) and shown in Figure 1:

$$\mu_{\max}(x)=\begin{cases} x & 0\le x\le 1 \\ 0 & \text{otherwise}\end{cases}$$

(3.1)

$$\mu_{\min}(x)=\begin{cases} -x+1 & 0\le x\le 1 \\ 0 & \text{otherwise}\end{cases}$$

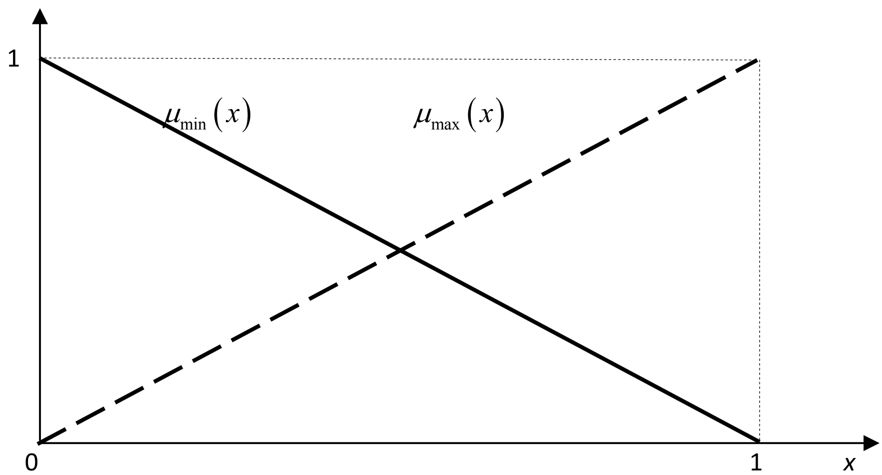

Figure 1: The membership functions of the maximizing and minimizing fuzzy sets

For fuzzy number A now we can make three values: the right value $\mu_R(A)$, the left value $\mu_L(A)$ and the total value $\mu_T(A)$. They are defined by expressions (Chen, Hwang, 1992):

$$\mu_R(A)=\max_x\left(\mu_{A\cap\max}(x)\right)=\max_x\left\{\min\left[\mu_A(x),\mu_{\max}(x)\right]\right\} \tag{3.2}$$

$$\mu_L(A)=\max_x\left(\mu_{A\cap\min}(x)\right)=\max_x\left\{\min\left[\mu_A(x),\mu_{\min}(x)\right]\right\} \tag{3.3}$$

$$\mu_T(A)=\frac{\mu_R(A)-\mu_L(A)+1}{2} \tag{3.4}$$

The right and left value are shown in Figure 3:

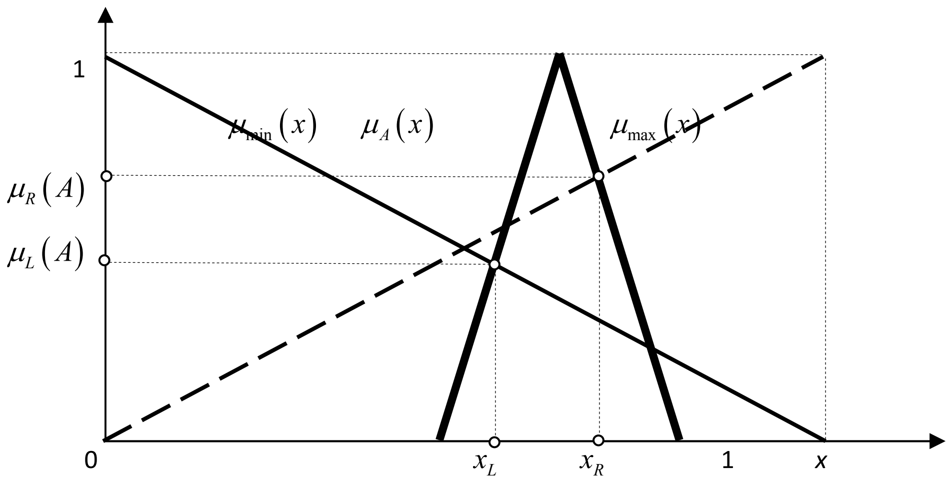

Figure 3: *The right ($\mu_R(A)$) and the left ($\mu_L(A)$) value of the fuzzy number A*

In the problems of the multiple attribute decision making with some fuzzy numbers is the first step, all the linguistic terms transform into crisp numbers according to the equations (3.2)-(3.4). With this transformation all the data in decision matrix *D* are crisp numbers. In the second step one of the classical multiattribute decision making methods, like this describing in chapter 2, for obtaining the final rank of the considered alternatives can be applied.

4. AN EXAMPLE

Let us take a simple example for organizing inner transport on area a hydroelectric power stationfactor under construction. Assume that the decision makers have to buy a new engines. He has four different suppliers and for different engins with similar characteristics. So, a total of four alternatives A_1, A_2, A_3, A_4 for buying the new engine have been considered. The alternatives differ in terms of: a) price, b) numbers of the safe testing into one year, c) fuel consumption and d) price of the maintenance. The alternative A_i means that the decision makers will buy the *i*-th engine ($i = 1,2,3,4$). For each of these alternatives four criteria were taken into consideration: X_1 - price (in 10^5 monetary units), X_2 - numbers of the safe testing into one year, X_3 - fuel consumption (in liters/100 km) and X_4 - price of the maintenance (in linguistic terms). The values x_{ij} that alternatives A_i , $i = 1, 2, 3, 4$ take according to criteria X_j , $j = 1, 2, 3, 4$ are given in the decision table (Table 4) and in the decision matrix *D.* The data x_{ij} for the objectives X_1, X_2, X_3 are crisp numbers, the data for X_4 are given in the linguistic terms (Usenik, 2003).

Table 4: *Values* x_{ij} *in the scheme of decision*

Criteria / Alternatives	X_1 - price 10^5 m. u.	X_2 - numbers of the safe testing	X_3 - fuel consumption	X_4 -price of maintenance 10^4 m. u.
A_1	4	4	20	High, cca 0,8
A_2	3	2	50	Low, cca 0,6
A_3	5	4	15	Medium, cca 0,7
A_4	6	3	55	very high, cca 0,9

Decision matrix is:

$$D=\begin{bmatrix} 4 & 4 & 20 & \text{high} \\ 3 & 2 & 50 & \text{low} \\ 5 & 4 & 15 & \text{medium} \\ 6 & 3 & 55 & \text{very high} \end{bmatrix} \tag{4.1}$$

According to the mathematical model we must first convert all linguistic terms (the data for X_4) into the corresponding fuzzy numbers. We have four fuzzy numbers for fuzzy variable “PRICE OF MAINTENANCE”: A (low), B (medium), C (high) and D (very high). We will assume the membership functions of all these fuzzy numbers are triangular.

In order for all the data in matrix D to be crisp, fuzzy numbers must be converted into the crisp scores. According to (3.2)-(3.4) the membership functions of the maximizing set, the minimizing set and the considered fuzzy numbers are calculated. In Figure 4 are presented membership functions of maximizing set, minimizing set and sets LOW, MEDIUM, HIGH, VERY_HIGH for fuzzy variable PRICE OF MAINTENANCE.

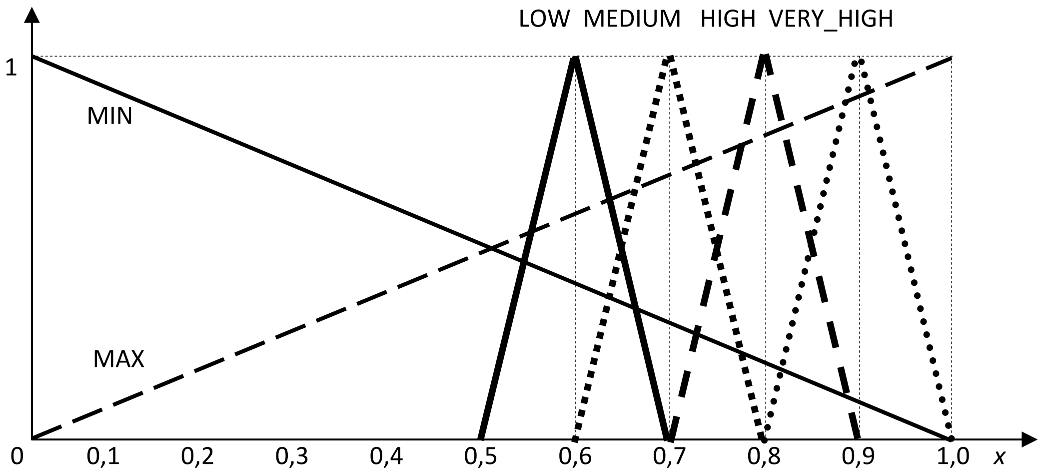

Figure 4: *Membership functions of maximizing set, minimizing set and sets A (LOW), B (MEDIUM), C (HIGH) and D (VERY_HIGH)*

Let us calculate scores $\mu_L(A)$, $\mu_R(A)$ and $\mu_T(A)$ for all the the fuzzy numbers.

From Figure 4 we can get the membership function of the fuzzy number *A* (LOW) as follows:

$$\mu_A(x)=\begin{cases} 0 & x \le 0,5 \\ 10x-5 & 0,5 \le x \le 0,6 \\ -10x+7 & 0,6 \le x \le 0,7 \\ 0 & x \ge 0,7 \end{cases} \tag{4.2}$$

Because the membership functions of the maximizing and minimizing sets are (see 3.1): $\mu_{\max}(x)=x$ and $\mu_{\min}(x)=-x+1$, we can get the numbers (abscises) x_L and x_R as follows:

$$10x_L-5=-x_L+1 \Rightarrow x_L=\frac{6}{11} \text{ and } \mu_L(A)=\frac{5}{11}$$

$$-10x_R+7=x_R \Rightarrow x_R=\frac{7}{11} \text{ and } \mu_R(A)=\frac{7}{11}$$

From (3.4) we have: $\mu_T(A)=\dfrac{\mu_R(A)-\mu_L(A)+1}{2}=\dfrac{13}{22}=0,591$.

In the same way: $\mu_T(B)=0,682$, $\mu_T(C)=0,773$, $\mu_T(D)=0,864$.

The calculated values of total scores are crisp numbers for objective X_4 and the decision matrix *D* (4.1) is now:

$$D=\begin{bmatrix} 4 & 4 & 20 & 0{,}773 \\ 3 & 2 & 50 & 0{,}591 \\ 5 & 4 & 15 & 0{,}682 \\ 6 & 3 & 55 & 0{,}864 \end{bmatrix} \tag{4.3}$$

The decision matrix *D* is now given by crisp numbers and we can rank the alternatives using one of the ordinary multiple-attribute decision-making methods. In this example is using the AHP method, describing in chapter 1.

At first we have to obtain the weights for all four objectives (characteristics) X_1, X_2, X_3, X_4.

Suppose that in our example we have the following pairwise comparison matrix for the objectives

$$A=\begin{bmatrix} 1 & \frac{1}{2} & \frac{1}{3} & 2 \\ 2 & 1 & \frac{1}{3} & 3 \\ 3 & 3 & 1 & 2 \\ \frac{1}{2} & \frac{1}{3} & \frac{1}{2} & 1 \end{bmatrix}$$

and its normalized form:

$$A_{\mathrm{NORM}}=\begin{bmatrix} 0{,}1538 & 0{,}1030 & 0{,}1542 & 0{,}2500 \\ 0{,}3077 & 0{,}2070 & 0{,}1542 & 0{,}3750 \\ 0{,}4616 & 0{,}6210 & 0{,}4611 & 0{,}2500 \\ 0{,}0769 & 0{,}0690 & 0{,}2305 & 0{,}1250 \end{bmatrix} \tag{4.4}$$

From (4.4) we have:

$$w_1=\frac{0{,}1538+0{,}1030+0{,}1542+0{,}2500}{4}=0{,}16525$$

$$w_2=\frac{0{,}3077+0{,}2070+0{,}1542+0{,}3750}{4}=0{,}26085$$

$$w_3=\frac{0{,}4616+0{,}6210+0{,}4611+0{,}2500}{4}=0{,}44842$$

$$w_4=\frac{0{,}0759+0{,}0690+0{,}2305+0{,}1250}{4}=0{,}12535$$

We must now check the consistency of our decision comparisons. This procedure consists from four steps. In the first step we compute Aw^T.

$$A\vec{w}^T = \begin{bmatrix} 1 & \frac{1}{2} & \frac{1}{3} & 2 \\ 2 & 1 & \frac{1}{3} & 3 \\ 3 & 3 & 1 & 2 \\ \frac{1}{2} & \frac{1}{3} & \frac{1}{2} & 1 \end{bmatrix} \begin{bmatrix} 0,16530 \\ 0,26090 \\ 0,44845 \\ 0,12535 \end{bmatrix} = \begin{bmatrix} 0,69585 \\ 1,11687 \\ 1,97742 \\ 0,51913 \end{bmatrix}$$

In step 2 we compute the number:

$$N = \frac{1}{n}\sum_{i=1}^{n} \frac{i\text{th entry in matrix } Aw^T}{i\text{th entry in } w^T} =$$
$$= \frac{1}{4}\left[\frac{0,69585}{0,16530} + \frac{1,11687}{0,26090} + \frac{1,97742}{0,44845} + \frac{0,51913}{0,12535}\right] = 4,2575$$

In step 3 we compute the consistency index *CI* as follows:

$$CI = \frac{\mathrm{N} - n}{n-1} = \frac{4,2575-4}{3} = 0,085$$

In step 4 we have to compare *CI* to the random index *RI* for the appropriate value of *n* (see Table 3).

In our example quotient $\frac{CI}{RI} = \frac{0,085}{0,90} < 0,10$, thus the weights w_1, w_2, w_3, w_4 are consistently.

We have now known weights for all the objectives, so we must on this basis rank the alternatives. The method used in the continuation is based on the simultaneous measurements of the distance of a particular alternative from the so called ideal and negative ideal solution. From the known decision matrix D the normalized decision matrix *R* and matrix V are calculated first. According to (2.3) – (2.5) we have:

$$R = \begin{bmatrix} 0,431 & 0,596 & 0,447 & 0,526 \\ 0,323 & 0,298 & 0,417 & 0,464 \\ 0,539 & 0,596 & 0,521 & 0,588 \\ 0,647 & 0,447 & 0,596 & 0,402 \end{bmatrix}$$

$$V = \begin{bmatrix} 0,071 & 0,155 & 0,114 & 0,066 \\ 0,053 & 0,078 & 0,286 & 0,058 \\ 0,089 & 0,155 & 0,086 & 0,074 \\ 0,107 & 0,117 & 0,314 & 0,050 \end{bmatrix}$$

From the matrix *V* the ideal solution A^* and the negative ideal solution A^- are determined. Because all of the criteria in our example are cost criteria, these solutions are defined with (2.6)-(2.7):

$$A^* = \{v_1^*, v_2^*, v_3^*, v_4^*\} = \{0,053;\ 0,078;\ 0,086;\ 0,050|\}$$

$$A^- = \{v_1^-, v_2^-, v_3^-, v_4^-\} = \{0,107;\ 0,155;\ 0,314;\ 0,074\}$$

The distances S_i^* and S_i^- are from (2.8)–(2.9):

$$S_1^* = 0,085\ , S_2^* = 0,200\ , S_3^* = 0,088\ , S_4^* = 0,238$$

$$S_1^- = 0,203\ ,\ S_2^- = 0,099\ , S_3^- = 0,232\ , S_4^- = 0,033$$

Relative closeness C_i^* of the alternatives A_i (*i = 1, 2, 3, 4*)to the ideal solution A^* are as follows: $C_1^* = 0,705$, $C_2^* = 0,331$, $C_3^* = 0,725$ and $C_4^* = 0,122$.

These values indicate that the alternatives are ranked in the following manner: A_3, A_1, A_2 and A_4 .

5. CONCLUSION

In this article the fuzzy approach to the multiattribute decision-making in control of logistics system was presented. The method for solving such problems consists of two steps: In the first step, the linguistic terms (fuzzy numbers) are transformed into crisp scores. After these transformations, all the data in the decision-making matrix *D* are crisp numbers. In the second step, one of the classical multiattribute decision-making methods for obtaining the final rank of the considered alternatives can be applied.

Every decision maker is every day and every moment faced with a hard task: to decide regularly, because bad decision could have a lot of bad consequences. Fuzzy approach is due to its simplicity quite good method for application also in cases of multiple attribute decision making.

REFERENCES

Bogataj, M., Usenik, J., 2005, Fuzzy approach to the spatial games in the total market, *Int., j. prod. econ.,* vol. 93-94, pp. 493-503.

Chen, S., Hwang, C., 1992, Fuzzy Multiple Attribute Decision Making, Methods and Application, Springer-Verlag, Berlin Heildelberg, pp. 465-486.

Ross, T., J., 2007, Fuzzy Logic with Engineering Applications, Second Edition, John Wiley & Sons Ltd., pp. 308-350.

Ruspini E.H., Bonissone P.P, Pedrycz W., 1998, Handbook of Fuzzy Computation, Institute of Physics Publishing Ltd, Bristol and Philadelphia, pp. F5.1:1-F5.1:14.

Teodorović, D., Vukadinović, K., 1998, Traffic Control and Transport Planning: A Fuzzy Sets and Neural Networks Approach, Kluwer Academical Publieshers, Boston, pp. 86-95.

Usenik, J.: 2003**,** Fuzzy Multiple-attribute Decision Making in logistics processes, Suvremeni promet (Modern Traffic), vol. 23, pp. 175-180.

Usenik, J., Bogataj, M., 2005, A fuzzy set approach for a location-inventory model, Transp. plan. technol., vol. 28, pp. 447-464.

Waters, D., 1997, Quantitative Methods for Business, second edition, Addison Wesley Longman Publishers Ltd., Essex, England, pp. 530-565.

Winston, W., L., 1994, Operations research, Applications and Algorithms, Duxbury Press, Belmont, California, pp. 771-804.

Zimmermann H.J., 1999, Practical Applications of Fuzzy technologies, Kluwer Academic Publishers, Boston, 68-84.

Zimmermann H.J., 2001, Fuzzy Set Theory and its Applications, Fourth Edition, Kluwer Academic Publishers, Boston, 352-370.

Journal of Energy Technology

JET Volume 1 (2008), p.p. 59 - 72

Issue 1, November 2008

www.fe.uni-mb.si/JET

NEW NUCLEAR POWER PLANT IN SLOVENIA

NOVA JEDRSKA ELEKTRARNA V SLOVENIJI

Martin Novšak, Jože Špiler, Robert Bergant, Tomaž Žagar
GEN energija, d.o.o.
Cesta 4. julija 42, 8270 Krško, Slovenia
martin.novsak@gen-energija.si, joze.spiler@gen-energija.si,
robert.bergant@gen-energija.si, tomaz.zagar@gen-energija.si

Keywords: GEN energija, nuclear power plant, electricity production, electricity consumption

Abstract

The Government of the Republic of Slovenia has adopted a document "Resolution on National Development Projects for the period 2007 – 2023" [1] in October 2006. Among several projects which all support sustainable development of Slovenia, an option of a new nuclear power plant was proposed. Thus, the Slovenian Government showed obvious intention and direction of Slovenian future electricity energy generation direction.

The supply of electricity has been sharpening in Slovenia in the last few years. For this situation two main reasons were identified. The first reason is lack of investment initiatives in new electricity production units in Slovenia. The electricity production of new hydropower plants added to Slovenian grid in the last ten years is not even covering the increase of domestic consumption. The second reason is growing of gross domestic product (GDP) and approaching to the life standard of developed EU countries. This has caused increased consumption of electricity. Since domestic electricity production does not follow the increased consumption, Slovenia already imports nearly a quarter of its needed electricity.

Slovenia would need 400 MWe of installed electrical power now for covering of its base load needs only. Based on recent electricity consumption forecasts, Slovenia will need 800 MWe of new base load electricity generation capacities by 2015 and 1500 MWe by 2025 respectively.

Besides high annual growth rate and high dependence on electricity import, a problem of relatively old power generation objects and realization of new energy and climate package for Europe exists. All together dictates our options for expansion of capacity production of the proposed Nuclear power plant Krško 2. Experience and knowledge of light water pressurized reactor can be effectively used at NPP Krško 2. Planned NPP Krško 2 would have between 1100 and 1600 MW of installed electrical power. If the decision on the national level is taken in 2009, construction could start in 2013 or 2014 and finish between 2017 and 2020.

Povzetek

Vlada Republike Slovenije je oktobra 2006 sprejela Resolucijo o ključnih nacionalnih razvojnih projektih za obdobje od 2007 do 2023 (ReNEP) ter med ukrepe in projekte, ki podpirajo doseganje trajnostnega razvoja Slovenije, uvrstila tudi možnost izgradnje drugega bloka jedrske elektrarne Krško. S tem je Vlada Republike Slovenije izkazala jasen interes in usmeritev pri reševanju energetske prihodnosti Slovenije.

Stanje na področju oskrbe z električno energijo se v zadnjih letih v Sloveniji zaostruje. S povečevanjem bruto domačega proizvoda in s približevanjem življenjskemu standardu razvitih članic EU se povečuje poraba električne energije. Proizvodnja električne energije iz novih elektrarn ne pokriva niti porasta porabe, ob tem pa je potrebno računati tudi na zapiranje starejših termoelektrarn. Ker domača proizvodnja ne sledi povečani porabi, Slovenija danes uvaža že skoraj četrtino električne energije.

Slovenija bi že danes potrebovala 400 MW inštalirane moči za pokrivaje lastne rabe pasovne energije. Glede na trenutno porabo elektrike bo v Sloveniji leta 2015 primanjkovalo približno 800 MW, leta 2025 pa že 1500 MW inštalirane moči za proizvodnjo pasovne energije.

Poleg visoke letne rasti porabe in velike odvisnosti od uvoza električne energije, pa je problem tudi relativno visoka starost energetskih objektov ter uresničevanje podnebno energetskega paketa EU. Na osnovi teh dejstev je potrebno resno razmišljati tudi o načrtovanju razširitve proizvodnih zmogljivosti jedrske elektrarne Krško z izgradnjo nove enote. Pri gradnji novega bloka jedrske elektrarne bo Slovenija lahko uporabila dosedanja znanja in izkušnje, ki jih ima s tlačno-vodnimi elektrarnami. Načrtovan drugi blok jedrske elektrarne bi imel inštalirano moč med 1100 in 1600 MW. Ob sprejetju odločitve za gradnjo na državni ravni v letu 2009 bi se gradnja lahko začela leta 2013 ali 2014 in končala med letoma 2017 in 2020.

----

1. INTRODUCTION

GEN energija is legal successor of all Slovenian investors into the existing NPP Krško (with registered company name Nuklearna elektrarna Krško (http://www.nek.si/)). The company was established by the Slovenian Government as ELES GEN in June 2001. After an arrangement of relations with the Republic of Croatia, the Republic of Slovenia transferred its share in NPP Krško (NEK) to the new founded company. In February 2006, the Government of the Republic of Slovenia has adopted a resolution on the free transfer of ELES GEN to the Republic of Slovenia. With the change of the company owner its vision and mission were redefined and in the same year the company was renamed to GEN energija.

Strategic goals of the GEN energija are the following:

- establishment of the Company as the independent provider of electric energy in Slovenia;
- increase in the extent of trading and expansion of the sale of electric energy on the retail market;
- formation of a flexible and compatible portfolio of production units and
- preservation of the nuclear option, high level of nuclear safety and public acceptability, protection of Slovenian interests and fulfillment of obligations according to the bilateral treaty on NPP Krško.

Electricity production company GEN energija is independent supplier of reliable and affordable electricity at competitive prices. The GEN energija group consists of GEN energija as the controlling company, and of five co-controlled companies: (i) the Nuclear Power Plant Krško (NEK) with 50% share, (ii) the retail and wholesale trading company GEN-I (http://www.gen-i.si/) with 50% share, (iii) gas fired power plant - Termoelektrarna Brestanica (http://www.teb.si/) with 100% share, (iv) hydropower plants on upper Sava river - Savske elektrane Ljubljana (http://www.sel.si/) with 79,5% share and (v) hydropower plants on lower Sava river - Hidroelektrarne na Spodnji Savi with 15,4% as shown in Figure 1.

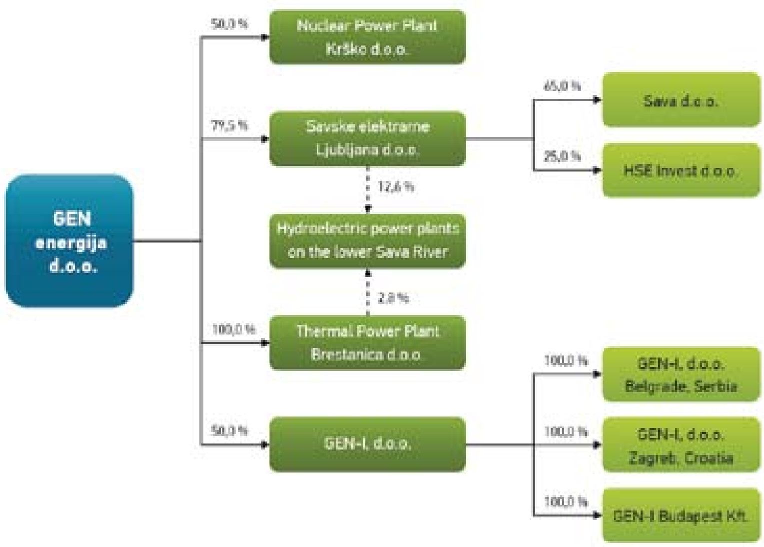

Figure 1: An organizational structure of GEN group.

Nuklearna elektrarna Krško (NEK) is the only power plant in Slovenia using nuclear energy for the commercial production of electric energy. It is the largest production unit in Slovenia, as the annual production ranges between 5.2 and 5.6 TWh, which means that, in accordance with the bilateral treaty between Slovenia and Croatia, between 2.6 and 2.8 TWh of electric energy is annually available for the Slovenian market. The second half of electric energy production belongs to the Croatian partner Hrvatska Elektroprivreda (HEP). In addition to the important share of the produced electric energy, another characteristic of the NEK is the extremely high reliability of production, which is especially important in ensuring the stability of the electric power system and reliable supply of customers.

2. ELECTRICITY PRODUCTION AND CONSUMPTION IN SLOVENIA

Slovenia has rather limited energy resources of its own, and imports all its oil and natural gas. Essentially all natural gas supplies origin from Russia and smaller part from Algeria. However, the country has diversified primary sources of electricity production. Roughly one third is produced by hydro power, another third by fossil fuels and the last third by nuclear power. The supply of electricity has been sharpening in Slovenia in the last years. The EIMV study [2] showed that growing of gross domestic product (GDP) and approaching to the life standard of developed EU countries caused increased consumption of electricity. Very strong correlation between increasing electricity consumption and increasing GDP is pointed out in Figure 2. It shows that the consumption growth is slightly below GDP growth in the last decade. This positive difference between gross domestic product growth and electricity consumption growth is a clear sign of successful and effective implementation of several energy efficiency measures already adopted in Slovenia.

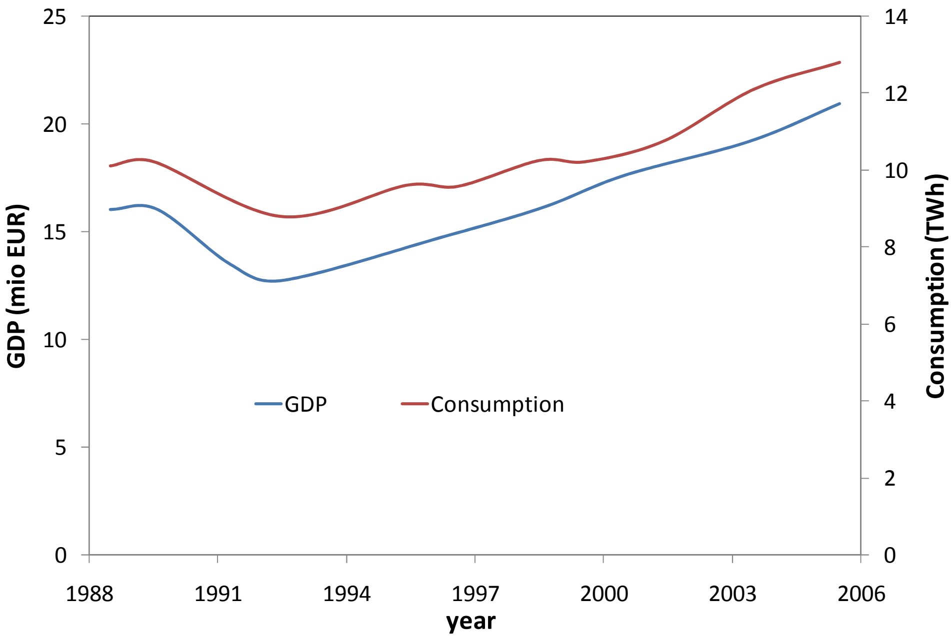

Figure 2: Correlation between electricity consumption and GDP (source: EIMV [2]).

Since domestic electricity production does not follow the increased consumption, Slovenia already imports nearly a quarter of needed electricity. In period between 1998 and 2003 total electricity production from NEK was consumed in Slovenia. This gave false impression that there was enough electricity for our needs. However, a real situation has shown right after the re-delivery of half electricity production to Croatia which happened in 2003. Thus Slovenia has become an importer of electricity. It imported 21% in 2003, around 15% in 2004, and more than 20% of total electricity consumption in 2005, 2006 and 2007. An increasing of electricity import is a result of electricity consumption growth which is in relation with economic growth and stagnation of new production capacities. Moreover, our neighbor countries (Italy, Austria, Hungary and Croatia) are also importers of electricity, which means that remaining generation capacity in the whole region is decreasing [3].

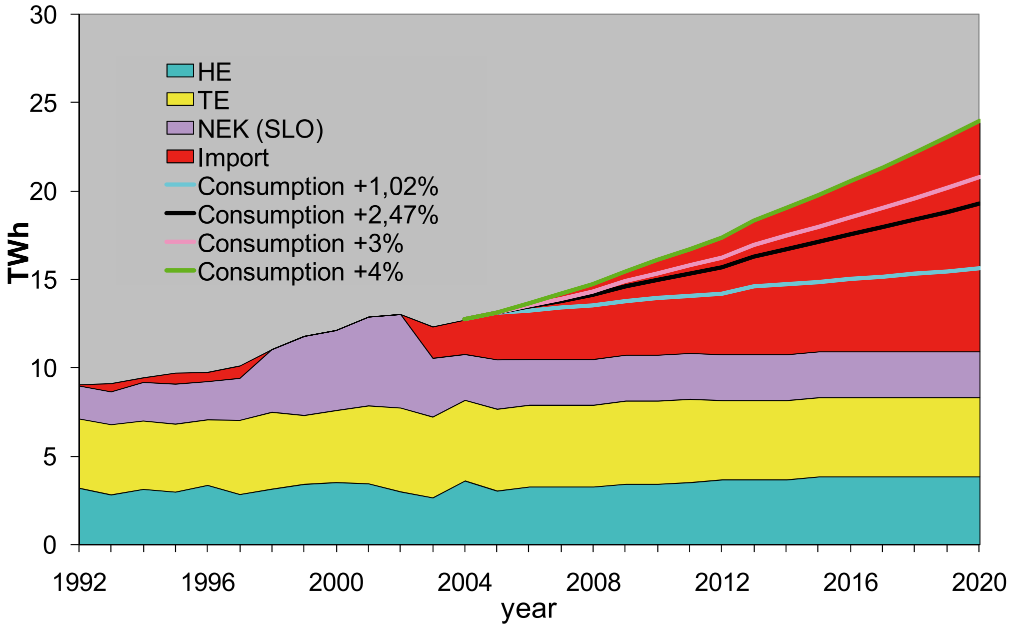

Figure 3: Consumption and production of electricity in Slovenia (source: IBE [4]).

Consumption and production of electricity in Slovenia from 1992 to 2006 and predictions from 2006 to 2020 are shown in Figure 3. Growth rates of 1,02% and 2,47% are taken from ReNEP (Resolucija o nacionalnem energetskem programu [5] or Resolution on National Energy Program). However, based on recent data and expected growth rate of GDP in Slovenia, even higher growth rate, between 3 and 4%, could be foreseen in the next years. These high consumption growth rates were first indicated in preliminary study prepared by IBE in 2006 [4]. A more detailed studies performed later showed the 4% consumption growth on a long term is less probable. The production capabilities shown in Figure 3 consider predicted life time of existing plants and all reconstructions and constructions according to IRN (Indikativni razvojni načrt [6] or Indicative development plan) and ReNEP [5].

Such strong import dependence has negative influence on a supply reliability, electricity price, competitive position and success of Slovenian economy in the Europe as well as in the world.

One of the options how to assure reliable supply and satisfactory price with insignificant influence on the environment, is construction of new nuclear power plant at Krško site. Slovenia already needs at least 400 MW of base load electricity for its own need. After completed construction of hydro power plant chain on lower Sava river and coal fired plant in Šoštanj (TEŠ VI) in 2015, the deficit will be still 800 MW of base load. If we take into consideration the same assumptions with 2,47% scenario, the deficit will increase to 1500 MW of base load in 2025. Since the deficit has to be replaced by minimal impact on the environment according to the Kyoto protocol and new energy and climate package for Europe, nuclear power plant as clear source to the environment and competitive source is the best choice.

For successful long-term planning of new generation capacity additional and more detailed consumption prediction studies were performed by EIMV and new scenarios were calculated in 2007 [2].These scenarios cover consumption prediction up to 2030 and they take into account several economic growth models, demographic developments, energy efficiency developments, national energy policy improvements, and other influencing factors such as climate change. Four scenarios developed by these studies are shown in Figure 4. All scenarios are based on 2004 and 2005 balance years, furthermore

- *NI scenario* as indicated in Figure 4 considers lower economic growth and intensive trends in the field of energy efficiency, intensive management and implementation of energy policy, rational and reasonable energy consumption and substitution of energy sources,
- *NZ scenario* as indicated in Figure 4 considers lower economic growth and moderate trends in the field of energy efficiency, moderate management and implementation of energy policy, rational and reasonable energy consumption and substitution of energy sources,
- *VI scenario* as indicated in Figure 4 means higher economic growth and intensive trends in the field of energy efficiency, intensive management and implementation of energy policy, rational and reasonable energy consumption and substitution of energy sources,
- *VZ scenario* as indicated in Figure 4 means higher economic growth and moderate trends in the field of energy efficiency, moderate management and implementation of energy policy, rational and reasonable energy consumption and substitution of energy sources.

Predictions above 2% (i.e. scenarios with higher economic growths) are more realistic at the moment, which was recently also confirmed by UCTE consumption forecasts [3] for Centre South region (Slovenia, Italy and Croatia) recently. UCTE forecasts 2% to 3% consumption growths for Slovenia.

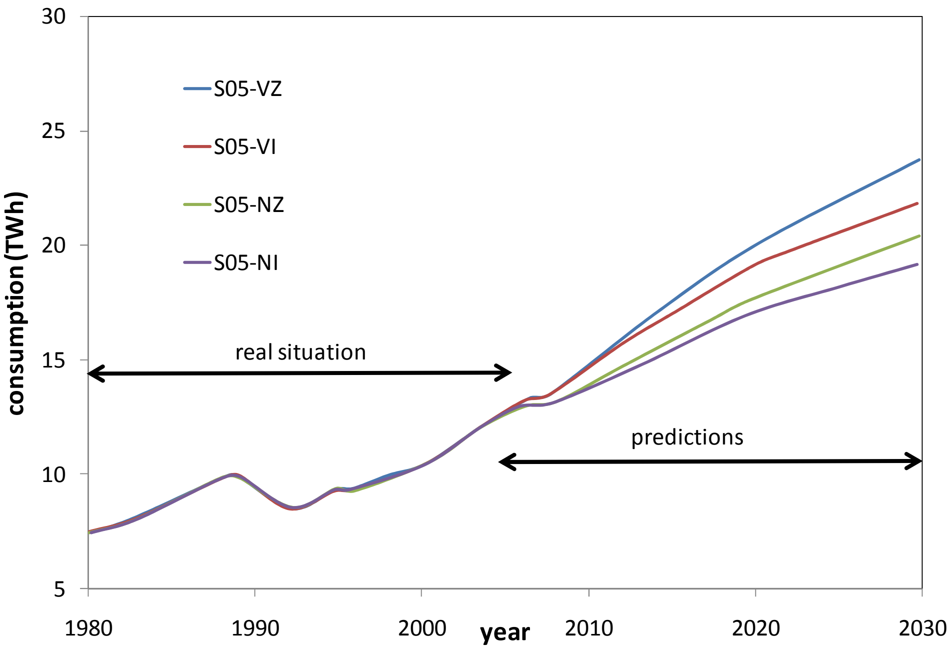

Figure 4: Different scenarios of future electricity consumption (source: EIMV [2]). For scenarios description see text above.

3. KRŠKO 2 PROJECT PLAN AND STATUS

Project NPP Krško 2 started in 2007 and it is divided into four general phases:

1. initiation phase includes project organization, studies and underlying documents preparations needed for decision making process, and other activities until firm building decision on national and local level is taken,
2. preparation phase includes spatial planning, planning of environmental impact assessment (EIA) program, EIA implementation and making of technical specifications for offers, negotiations and signing of the contract for building,
3. construction phase includes making of project documentations for building, construction and fitting of equipment as well as attaining of construction and operational license and,
4. operational phase which comprises of 60 years of commercial operation.

There are several (hundred) milestones in a new NPP construction project. It is not the purpose of this paper to describe those milestones in details. Five major milestones important for overall picture of the NPP Krško 2 project are presented in Figure 5. Activities leading to a decision on national level are grouped in the first period also called preparation period. After the decision is accepted on the national level, project advances into implementation period leading to successful long-term operation.

Major milestones in the preparation period are the completion of major analyses and evaluations needed for decision making process. This should be achieved in 2009. Second milestone in the preparation period is sitting. Decision on the project could be accepted when a preferred site (one out of two preferred site variants) is identified and when all needed analyses and evaluations are completed. These analyses and evaluations are required foundations for decision making process on the national level. Currently it is expected that the decision will be formed in a resolution, act or special law accepted in parliament.

After the decision in 2010, the project advances in the implementation period. All dates after the initiation of the implementation period are relative and are connected to the date of formal decision. If the decision is taken in 2009 the construction could be completed between 2017 and 2020. Delays in the decision making process have important influence on the construction schedule. Short delays in the decision could result in longer delays in completion date. Every year new NPP projects in the world are announced, this presents new orders for the equipment suppliers. Current market situation is leading to the situations in which later orders reflect in significantly less favorable delivery dates. This unfavorable situation will be somewhat relaxed with the adaptation of the suppliers to the new market situation with new manufacturing capabilities. In any case, it is expected the demand for new nuclear power plants in the mid term future will not be matched completely with the supply.

Implementation period is initiated with bidding and consequent negotiations with potential suppliers. Pre-construction activities on the site (site preparation activities) are also initiated in this period. Preparation phase ends with construction permit, which is next important milestone. With construction permit the construction phase is initiated with first concrete pouring. Construction ends with test operation. Final phase of the project is successful operation phase.

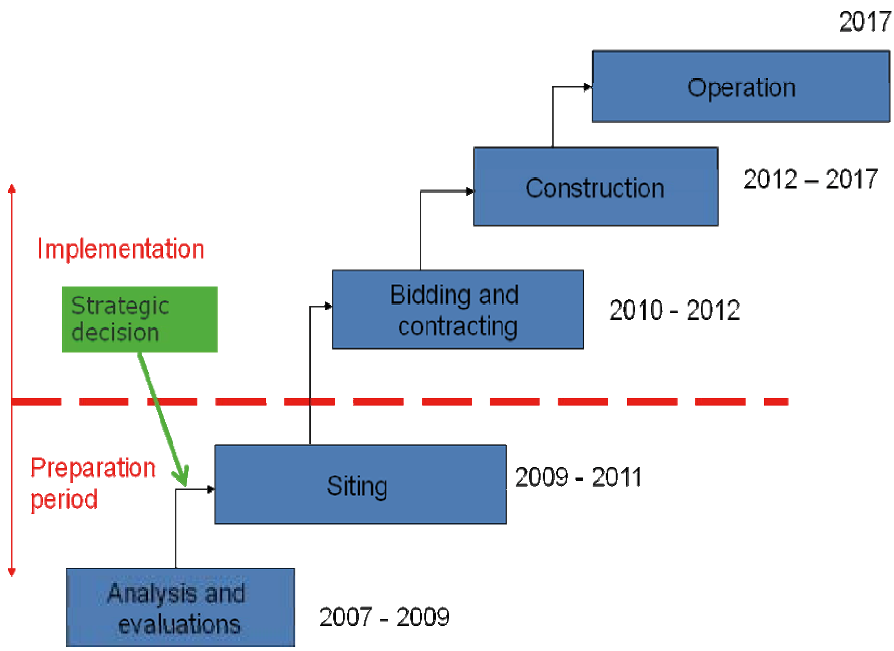

Figure 5: NPP Krško 2 major milestones. Indicated dates are only illustrative.

The project Krško 2 is currently in the initiation phase. Before spatial planning process takes place, several activities have to be performed. Many of them are already implemented, while minor are still in the progress. The project Krško 2 started with an *Identification document for project investment* [7]. Its purpose was to identify first description and estimation of the project investment as well as to give further bases for investment continuation. A *Spatial reservation document* [8] identified two possible locations, i.e. east (downstream) and west (upstream) from the existing NPP Krško. The purpose of a study on *Optimal covering scenario of electricity consumption in Slovenia up to 2030* [2] was to justify a need of new power unit in Slovenia. The study compared different scenarios possible in Slovenia and it came to the conclusion that nuclear scenario is an optimal solution from the sustainable point of view. Later on, a review [9] of aforementioned study was done where scenarios where three distinct scenarios were determined based on the technology used. The three scenarios were: a) business as usual with no new investments, old coal fired power plants shut down and the import is increased; b) scenario based on imported coal and gas, with refurbishment of old coal power plants and the construction of new coal and gas fired plants; and c) scenario with new NPP and with refurbishment of old coal fired plants. In all scenarios the life extension of the existing NPP Krško was assumed. Besides obvious conclusion already emphasized in the original study some other advantages of nuclear technology were indicated. The most important ones are strategic importance for diversity of primary energy sources, a reduction of greenhouse gases, nuclear fuel recognized as home energy source, electricity price not strongly correlated to the fuel price. A summary of both studies with very detailed analysis of all possible technology in regard to Slovenian case is presented in *An analysis of development possibilities* [10]. The study will be one of the key documents which will be sent to the Slovenian Government in order to make a political decision regarding the Krško 2 nuclear power plant project. As continuation of the identification document project investment *A pre-investment project* [11] was performed. Detailed economic, environmental and technological analysis preferred four out of several different reactors that need to be compared in all next studies. The list of the preferred reactors is as follows:

- EPR provided by Areva,
- EU-APWR by Mitsubishi,
- Atmea1 by ATMEA and
- AP1000 by Westinghouse

where first two have an electrical output between 1600 and 1700 MWe, and the second two between 1100 and 1200 MWe. All reactors are classified as light water pressurized reactor of the third generation.

The efficient use of energy is one of the topic issues of the new EU proposal on energy and climate change package released in January 2008. Therefore *the study on waste heat utilization of the new nuclear power plant Krško 2* [12] was performed. It analyzed possibilities of using waste heat for district heating as well as district cooling in nearby cities. Besides higher overall efficiency also a reduction of CO2 is considerable.

Macro-economic effects of construction and operation of NPP Krško 2 [13] showed an influence on economic development of local community as well as on Slovenia. The Krško 2 project would involve several hundred people plus another several thousand during construction of the plant and all that would have great impact on Slovenian GDP rise as well as economic

----

competitiveness in the future. *An economic and social development impact analysis of nuclear objects on local community and region* [14] confirmed some of the above results and in addition found out many positive impacts on social development of the region.

Besides activities which are already completed, many activities are still going on. *Geotechnical, geological and seismological evaluations for NPP Krško 2 (GG&S)* which started at the end of 2007 is the most extensive study by now. It will show if foreseen locations fulfill very stringent requirements for construction of nuclear power plant, and furthermore which of both locations exhibits better characteristics from the geotechnical, geological and seismological point of view. GEN energija is responsible to review and comment aforementioned study during the entire period of execution. Therefore, we outsourced an independent reviewer who has enough knowledge in relevant fields to competently review and consult us. Under the project GG&S also *an influence of new attenuations on design earthquake parameters* [15] was performed. Different declination models were used to analyze the earthquake propagation and soil and structures interactions at the Krško site. Based on obtained results it can be speculated that seismo-tectonic safety analysis which would use newer models would most probably give slightly different design earthquake parameters.

A public relation as well as social acceptability was recognized as one of the key process and key risks in the Krško 2 project. A project considering *social environment analysis and implementation of managing relations with public* is almost finished. The basic purpose of the study is to recognize and establish all needed models for effective and efficient relation with public which can considerable reduce the risk of unsuccessful project implementation. All other processes were identified in *Development of quality management system for the new Krško 2 nuclear power plant project*. Its purpose is to establish quality policy, manual, processes and procedures in accordance to ISO standard and in addition to nuclear safety requirements for safety related items. In order to achieve higher quality *an independent consultancy on quality management system* was assigned.

A conceptual design of NPP Krško 2 was assigned to get very good technical basis for spatial planning process which will take place in the preparation phase. In addition also plant parameter envelope (PPE) with entire spectrum of all important parameters will be compiled. A part of the study is also a description of four different reactors which was previously described in *Technology description* [16].

An environmental impact report (EIR) as part of the spatial planning will be very important. But before EIR will start, *a strategic environmental report* has to be performed. The purpose of the study is to prepare a preliminary report on environmental impacts of different energy technology options for Slovenia. Nuclear option will be presented and compared to other options currently discussed in Slovenia. The report of this study will be also a consultation document for initiating broad public consultation process.

Used nuclear fuel management has to be planned and performed with great details. In addition this topic is also very high on public debate agendas. Therefore a study *Used nuclear fuel management strategies for Slovenia* was started. The purpose of the study is to present the options and possibilities on management strategies of recyclable fissile and fertile materials in used nuclear fuel to the government of the Republic of Slovenia and all other interested parties. Currently the only option seriously considered in the official planning process was the direct

----

disposal. All other possibilities were overlooked. The above mentioned study is intended to study also other options including partially or fully closed fuel cycles.

Concerning the environment, a cooling of the plant and consequently warming of the environment is the only effect of a nuclear power plant on the environment. *The feasibility study and optimization of cooling towers at new nuclear plant* will highlight the advantages and disadvantages of presented designs and suggestions for optimal solution from environmental, technological and economic point of view.

For the foreseen NPP Krško 2 two locations are taken into consideration. Both are situated on the left Sava river bank directly upstream and downstream of the existing Krško NPP site. The selection of the site will be based on the results of many studies already mentioned and on the results of broad public consultation process. GG&S and flood protection studies will be probably one of the more important studies in this process. Public consultation process will be organized according to the Slovenian spatial planning laws and EU directives. Currently specific site is not selected jet. For this reason a computerized visualization of proposed NPP for downstream or east location related to existing NPP is shown on Figure 6.

Figure 6: A schematic view of new NPP Krško 2 located at potential downstream location of Sava river (source: Logon [17]). Site selection is a result of a formal process with included public consultation process. Before the end of the process no specific site is final.

4. CONCLUSION

Decades of stagnation in a building of new power plants drives Slovenia as well as most other countries in the situation where a gap between consumption and production of electricity become significant. The issue has become so serious that the energy policy has been placed on

----

the top of all political debates. Slovenia has already adopted some of the measures, i.e. the program of efficient use of the energy, but we have to know that this can only reduce the growth of electricity consumption, especially if we take into account a closing of old capacities after 2015. The Slovenian Government will have to take a responsibility for selection of the most suitable direction which will fulfill the requirements and expectations of the economic competitiveness, environment and social development regarding the natural possibilities of the country. Several different studies which all consider sustainable development have shown that development scenarios including new nuclear power plant have several advantages before non-nuclear ones.

Different scenarios up to 2030 were analyzed and they all show that a need for electricity will rise from 13 TWh in 2008 to 17 TWh in low consumption scenario and to more than 20 TWh in high consumption scenario in 2020 respectively. If nothing will be done then even worse situation is foreseen for the end of 2030.

Slovenia could use current knowledge and experience which it has with light water pressurized reactors. Different light water pressurized reactors with installed power between 1100 MWe and 1700 MWe have been analyzed.

The Krško 2 project is very much dependent on a political decision. If the decision for the construction and operation of new NPP in Slovenia is taken in 2009 the construction could start in 2013 or 2014 and finish between 2017 and 2020. Delays in the decision making process have important influence on the construction schedule.

New NPP means great challenge and acknowledgement for previous work of nuclear experts in Slovenia. Planning and construction of new NPP would be a great opportunity for development of nuclear option which means new labor resources for nuclear engineers and much better promise for their employment as well as motivation.

REFERENCES

[1] "Resolucija o nacionalnih razvojnih projektih za obdobje 2007-2023 ReNRP", Urad Vlade RS za informiranje, Ljubljana, October 2006.

[2] "Optimalni scenarij pokrivanja porabe v Republiki Sloveniji s proizvodnjimi viri do leta 2030", Študija št. 1848, EIMV, Ljubljana, 2007.

[3] "UCTE System Adequacy Forecast 2008 - 2020", Union for the Coordination of Transmission and Electricity, Brussels, January 2008.

[4] "Postavitev nove jedrske elektrarne v Sloveniji", Dokument identifikacije investicijskega projekta, NNE2---0X/01, IBE, Ljubljana, August 2006.

[5] "Resolucija o nacionalnem energetskem programu ReNEP", Uradni list Republike Slovenije Št. 57/2004

[6] "Indikativni razvojni načrt (IRN) energetskega sektorja", elaborate, IBE, 2005.

----

[7] Dokument identifikacije investicijskega projekta, IBE, Ljubljana, 2006.

[8] Izdelava dokumentacije za predlog za rezervacijo prostora za drugo jedrsko elektrarno na lokaciji Krško, IBE, Ljubljana, 2007.

[9] Recenzija študije Optimalni scenariji pokrivanja porabe v Republiki Sloveniji s proizvodnjimi viri, Fakultata za elektrotehniko, Ljubljana, 2008.

[10] Analiza razvojnih možnosti, Elek, Ljubljana, 2008.

[11] Predinvesticijska zasnova, HSE Invest, Maribor, 2008.

[12] Study on waste heat utilization of the new nuclear power plant Krško 2, Imuthes, Gradz, 2008.

[13] Makroekonomski učinki gradnje in delovanja JE Krško 2, Ekonomski institute pravne fakultete, Ljubljana, 2008.

[14] Analiza ekonomskih in socioloških razvojnih vplivov jedrskih energetskih objektov na lokalno skupnost in regionalni proctor, KIN.PS, 2008.

[15] Vplivi novih atenuacij na projektne potresne parameter na lokaciji Krško 2, Fakulteta za gradbeništvo in geodezijo, Ljubljana, 2007.

[16] Opis tehnologij potencialnih reaktorjev za project druge enote jedrske elektrarne Krško – Krško 2, ICJT, Ljubljana, 2008.

[17] "Izdelava računalniških vizualizacij in interaktivne vizualne simulacije dveh variant postavitve nove JEK", Logon, Ljubljana, 2007.

AUTHOR INSTRUCTIONS (MAIN TITLE)

SLOVENIAN TITLE

Authors, Corresponding author[ℜ]

Key words: (Up to 10 keywords)

Abstract

Abstract should be up to 500 words long, with no pictures, photos, equations, tables, only text.

Povzetek

(In Slovenian language)

Submission of Manuscripts: All manuscripts must be submitted in English by e-mail to the editorial office at JET-editors@uni-mb.si to ensure fast processing. Instructions for authors are also available online at www.fe.uni-mb.si/JET .

Preparation of manuscripts: Manuscripts must be typed in English in prescribed journal form(Word editor). Word template is available at Journal Home page.

Title page consists of Main title in English and Slovenian language; Author(s) name(s) and address, affiliation, E-mail address, telephone and fax numbers of author(s). Corresponding author must be indicated.

Main title: should be cantered and written with capital letters (ARIAL **bold** 18 pt).

Key words: A list of 3 up to 6 key words is essential for indexing purposes. (CALIBRI 10pt)

[ℜ] Corresponding author: Title, Name and Surname, Tel.: +XXX x xxx xxx, Fax: +XXX x xxx xxx, Mailing address: xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx

E-mail address: email@xxx.xx

Main text should be structured logically in chapters, second chapters and thirds chapters. Type of letters is Calibri, 10pt, full justified.

Units and abbreviations: Required are SI units. Abbreviations must be given in text when firstly t mentioned.

Proofreading: The proof will be send by e-mail to the corresponding author that is required to make their proof corrections on a print-out of the article in pdf format. Corresponding author is responsible to introduce corrections data in the paper. The Editors are not responsible for damage or loss of manuscripts submitted. Contributions are advised to keep copies of their manuscript, illustrations and all other materials.

The statements, opinions and data contained in this publication are solely those of the individual authors and not of the publisher and the Editors. Neither the publisher nor the Editors can accept any legal responsibility for errors that could appeared during the process.

Copyright: Submissions of a publication article implies transfer of the copyright from the author(s) to the publisher upon acceptance of the paper. Accepted papers become the permanent property of "Journal of Energy Technology". All articles published in this journal are protected by copyright, which covers the exclusive rights to reproduce and distribute the article as well as all translation rights. No material can be published without written permission of the publisher.

Chapters examples:

1. INTRODUCTION (Main Chapter)

1.1 Second Chapter

1.1.1 Third Chapter

Example of Equation:

$$c = \sqrt{a^2 + b^2} \tag{1.1}$$

Tables should have a legend that includes the title of the table at the top of the table. Each table should be cited in the text.

Table legend example:

Table 1: *Name of the table (centred, on top of the table)*

Figures and images should be labelled sequentially numbered (Arabic numbers) and cited in the text. The legend should be below the image, picture, photo or drawing.

Figure legend example:

Figure 1: *Name of the figure (centred, on bottom of image, photo, or drawing)*

REFERENCES

[1] **Name. Surname:** *Title,* Publisher, p.p., Year of Publication

Example of reference-1 citation: In text, Predin, [1], text continue. **(Reference number order!)**

Or

Surname, Name, Year of Publication, *Title,* Publisher, p.p**.** **(Alphabetic ordering!)**

Example of reference-2 citation: In text, (*Predin, 2008*), text continue.

JET Journal of ENERGY TECHNOLOGY Vol. 1/1 2008 UNIVERSITY OF MARIBOR, FACULTY OF ENERGY TECHNOLOGY

ENERGIJA

FACULTY OF ENERGY TECHNOLOGY

skupina group

With perfect respect for diversity!

ISSN 1855-5748