AN APPLICATION OF IRIDM IN THE DECISION MAKING PROCESS ON FUEL CONVERSION OF THE MARIA REACTOR

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Abstract. *Poland, when acceded to GTRI (Global Threat Reduction Initiative) in 2004, has committed to convert the nuclear fuel of the Research Reactor MARIA, operated by the National Centre for Nuclear Research (NCBJ) in Świerk. The conversion means giving up of high enriched uranium fuel containing 36% of U-235, which was used so far, and replacing it with the low enriched uranium fuel (19.7% U-235). This article describes the potential usability of the Integrated Risk Informed Decision Making (IRIDM) methodology in optimization of the fuel conversion procedure.*

Keywords: nuclear safety, Integrated Risk Informed Decision Making (IRIDM), Research Reactor MARIA, Global Threat Reduction Initiative (GTRI), nuclear fuel conversion

ZASTOSOWANIE IRIDM W PROCESIE DECYZYJNYM DOTYCZĄCYM KONWERSJI PALIWA W REAKTORZE MARIA

Streszczenie. *Polska, przystępując w 2004 roku do programu GTRI (Inicjatywa Redukcji Zagrożeń Globalnych), zobowiązała się do konwersji paliwa jądrowego w reaktorze badawczym MARIA, eksploatowanym przez Narodowe Centrum Badań Jądrowych (NCBJ) w Świerku. Konwersja ta oznacza rezygnację z dotychczas użytkowanego paliwa, zawierającego 36% U-235 i zastąpienie go paliwem nisko wzbogaconym (19.7% U-235). Niniejszy artykuł opisuje potencjalne zastosowanie zintegrowanego procesu decyzyjnego (IRIDM) w optymalizacji procedury konwersji paliwa.*

Słowa kluczowe: bezpieczeństwo jądrowe, zintegrowany proces decyzyjny, Reaktor Badawczy MARIA, Inicjatywa Redukcji Zagrożeń Globalnych (GTRI), konwersja paliwa

Introduction

The regulatory body responsible for nuclear issues in Poland is the National Atomic Energy Agency (NAEA). The mission of this organization is to make decisions on the nuclear facilities and activities within the country, including technology licensing, developing of the nuclear regulations and conducting technical inspections, in order to ensure public safety and environmental protection. In carrying out its responsibilities, NAEA cooperates with external organizations, i.e. the International Atomic Energy Agency (IAEA) and U.S. Nuclear Regulatory Commission (U.S. NRC), in the field of development and implementation of the nuclear safety and security standards.

In 2004 Poland has also officially acceded to Global Threat Reduction Initiative (GTRI) established by the U.S. National Nuclear Security Administration (NNSA). The main aim of this programme is to identify, secure, remove and/or facilitate the disposition of the high risk vulnerable nuclear and radiological materials around the world that pose a threat to the international community. Otherwise these materials could potentially be used by terrorists to make an improvised nuclear device, a radiological dispersal device or a dirty bomb. One of the main GTRI goals is to convert research reactors and isotope production facilities from the use of highly enriched uranium (HEU) to low enriched uranium (LEU), which cannot be used to make a nuclear weapon even if it falls into the wrong hands. So far under the GTRI project 82 research reactors around the world that used HEU have converted to LEU fuel or been verified as shut down. It means that more than 3450 kilograms of HEU and plutonium – enough for more than 135 nuclear weapons – have been removed [14].

Poland, when acceded to GTRI project, has also committed to convert the nuclear fuel of the Research Reactor MARIA, operated by the National Centre for Nuclear Research (NCBJ) in Świerk. The conversion means giving up of MR-6 – Russian HEU fuel containing 36% of U-235, which was used so far, and replacing it with CERCA LEU (19.7% U-235) fuel, manufactured in France. However, due to the significant differences in physical characteristics between the previously used and the new fuel elements, the conversion is a very complex process. Change of the uranium enrichment as well as modification of the fuel element design leads to changes of physical parameters of the reactor core. Therefore, when the decision on the fuel conversion has been made, one needs to answer question how to perform this process in an optimal manner. Basic criterion is to maintain the previous operating parameters of the reactor while meeting the safety requirements after the conversion.

However, economic costs as well as time and specialized resources have to be also taken into account in the decision making. In such cases, when non-routine decision has to be made, usage of the IRIDM (Integrated Risk Informed Decision Making) methodology is recommended by the IAEA [13]. This article describes the potential application of IRIDM in optimization of fuel conversion process of the MARIA reactor.

1. The Research Reactor MARIA

The Research Reactor MARIA is a multi-purpose, high flux, pool type reactor, moderated with water and beryllium with graphite reflector and pressurized channels consisting of 22 concentric six-tube assemblies of fuel elements. The active length of the fuel assemblies is 1000 mm. The reactor was designed with a high degree of application flexibility and it has been using the high enriched uranium fuel (UO_2-Al alloy) with aluminium cladding since it began the operation. The fuel channels are situated in a matrix containing beryllium blocks and enclosed in a lateral reflector made of graphite blocks in aluminium cans. MARIA is equipped with vertical channels for irradiation of target materials, a rabbit system for short irradiations and 7 horizontal neutron beam channels. The nominal power of reactor is 30 MW_t while the thermal neutron flux density is $4.0 \cdot 10^{14}$ neutrons/cm^2s.

The Research Reactor MARIA went critical for the first time in December 1974 and remained in operation until 1985 when it was shut down for modernization, that encompassed upgrading and refurbishment of the technological systems. In particular, efficiency of the ventilation and cooling system was improved. In 1993 the reactor has been put into operation again [6].

Currently the main area of its application is the radioisotopes production. It should be highlighted here that MARIA is one of the few reactors able to produce Mo-99 on a global scale. Providing a regular supply of molybdenum is essential for the diagnosis of cancer in medical centres all over the world [5]. This reactor is also suitable for testing of fuel and materials for the nuclear power engineering, neutron studies (radiography, activation analysis and transmutation doping) and for the scientific research in the field of condensed matter physics.

Moreover, implementation of a new experimental medical installation inside of the reactor is being considered, i.e. the Boron-Neutron Capture Therapy (BNCT) which is an experimental radiotherapy technique used to treat the most aggressive types of brain tumours that cannot be surgically removed from the human body. To date, clinical trials of that therapy have been initiated at only a handful of research reactors around the world [4, 11].

2. The fuel conversion procedure

The fuel conversion process, which leads to decrease of the enrichment from 36% to 19.7% of U-235, is posing a problem. Namely, in order to maintain approximately the same thermal power after the conversion, the volume of fuel itself has to be greater. For that reason the present fuel channel configuration – that bases on 6 concentric tubes (Fig. 1) – will be replaced with a new one, which consists of only 5 tubes but with different diameters and thicknesses. Moreover, some extra internals for stiffening of the structure will be also installed.

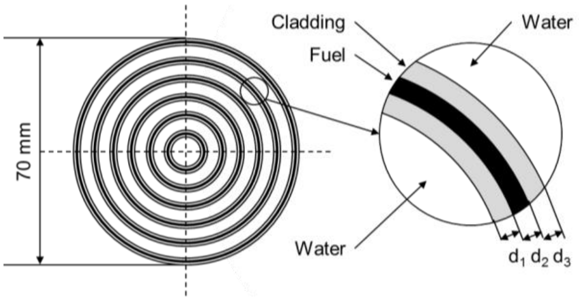

Fig. 1. Horizontal cross section of the high enriched uranium (HEU) fuel element

Since the new fuel elements have a different design it was necessary to qualify them for usage in the MARIA reactor by direct irradiation of two trial assemblies in the core, under normal operational conditions. It was preceded by calculation analyses and measurements. First of all the neutronic and core reactivity characteristics for a configuration with the trial LEU assemblies were compared to the core with HEU fuel. The calculations did not show significant differences between these two cases [8].

The thermal hydraulic analysis shows that the cladding temperature for both types of fuel elements are almost the same, e.g. maximum cladding temperature on the internal surface of the tube is 425 K and 426 K for LEU and HEU, respectively. However, the maximum heat flux on the external wall of the fuel tube is 2,61 MW/m^2 and 2,04 MW/m^2 for the LEU and HEU fuel, respectively. Moreover, the data acquired from the performed measurements point out that the coefficient of hydraulic resistance for LEU fuel elements exceeds by around 30% the resistance coefficient for the Russian HEU fuel [3].

The required coolant flow rate through the new LEU fuel channel is at least 30 m^3/h while in the HEU fuel it is equal to 25 m^3/h. This difference implies the necessity of increasing the mass flow in the new channels up to 120% of previous nominal flow. Since the existing infrastructure is not sufficient to increase the mass flow, this process requires replacement of the primary cooling channel pumps. It complicates the whole procedure and makes the full conversion impossible without expensive investments. However, the experiment which has been carried out, shows a possibility of initiating the partial conversion process even before modernization of the pump system [7]. Thus the whole procedure would proceed in a gradual way and the most burned-up HEU fuel would be unloaded first.

Such a solution seems to be optimal from the utility point of view, but the final decision and ultimate responsibility in such a case lies always in the competence of the NAEA. The NAEA, while making decisions on nuclear installations, firstly shall be guided by the public safety. Thus the transparency and auditability of the decisions is highly expected by people. In order to meet this challenge it is recommended to implement IRIDM methodology within the regulatory organization.

3. Framework of the IRIDM process

According to the basic framework of IRIDM, proposed by the IAEA, the clear definition of issue to be resolved is crucial in identifying which elements or information are relevant in decision making. Thus, this is the first step of the IRIDM process (Fig. 2).

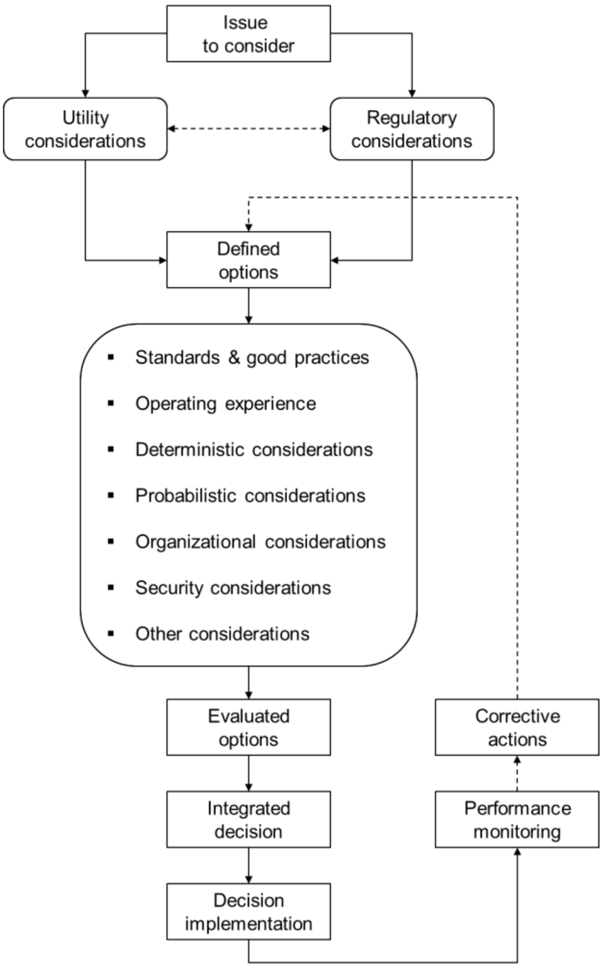

Fig. 2. Organizational framework and key elements of the IRIDM process [cf. 9, 13]

After defining the problem, consideration must be given to the requirements of both regulatory body and utility in order to draft a preliminary set of options that potentially could solve the issue. However, to make the final decision and choose one from the preliminary set of options, specified elements (i.e. the standards and good practices, operating experience, deterministic and probabilistic considerations, organizational and security systems, research and economic insights) should be accounted for. All these elements have been described in detail in a separate article of the authors [2].

Relative importance of each element depends upon the decision to be made and should be weighted either qualitatively or quantitatively. This process leads to evaluation and to reduction of the preliminary set of options. Finally, one of them should be chosen, implemented and monitored. If the performance of just implemented decision is not satisfactory corrective actions should be undertaken and the list of options needs to be redefined.

4. Potential application of IRIDM

Until now, the activities of the NAEA were based mainly on the deterministic approach and engineering judgment. The IRIDM methodology is not yet a mandatory formula for the decision making process, but its implementation is considered to be a valuable asset due to its well organized structure, consistency and an approach easy to follow step by step.

The very first case study made with use of the IRIDM methods was to determine the best way of the MARIA reactor core conversion process. According to the IRIDM methodology, at the point when the issue to be resolved is known, one needs to define some options overcoming the problem. This means that either the regulatory body or the utility has to consider and outline the possible solutions.

In this case, NAEA preferences were as follows. First of all, the new fuel means either the change in reactor core configuration (i.e. structure of the fuel channels) or in cooling circuit (i.e. higher efficiency of the feed-water pumps). This can be qualified as a major change and thus it requires additional analyses that will prove the safety margins. The results together with technical data should be then submitted to the President of NAEA in a form of annex to the Safety Analysis Report of the reactor. Additionally, the document should contain an impact study of the LEU fuel introduction on reactor operation (i.e. insufficient coolant flow, neutronic balance aspects etc.) during the conversion period. One should remember that the gradual way of core conversion means handling two types of fuel at the same time. It requires more complex safety analyses but on the other hand it gives a chance to avoid radical change of the core matrix that could lead either to technical or economical maintenance difficulties.

Beyond safety aspects, from the utility point of view, it is highly important to maintain production of the isotopes. For certain types of them it is necessary to maintain proper neutron flux in the core, which requires operation with high power of reactor. Finally, in order to deal with the issue, NAEA has defined three options to be considered (Tab. 1). The only difference between them is the time when the conversion may begin. Each option assumes the need for making the safety analysis for reactor operating either with new LEU fuel or with new pumps, but for option 1 and 2 it is necessary to make additional analyses in case of old pumps, i.e. under condition of insufficient amount of coolant provided to the new LEU fuel channels.

Table 1. Preliminary set of options prepared by the National Atomic Energy Agency

Option number (i)	Option description
1	Permission may be granted for partial core conversion before change of the pumps (with higher flow rate) without any additional criteria
2	Permission may be granted for partial core conversion before change of the pumps (with higher flow rate) but with additional criteria
3	Rejection of partial core conversion before change of the pumps

The above considerations should now be thoroughly checked, by the dedicated multidisciplinary IRIDM team. The team members were recruited from two divisions of the Nuclear Safety Department (at NAEA), each of them with a suitable knowledge of the facility. It should be stressed out that designated NAEA experts have an experience with the core conversion. The first successful core conversion of the MARIA reactor was conducted in 2002. At that time the enrichment of the HEU fuel was decreased from 80% to 36% of U-235. This process revealed also some aspects, which were not accounted for, but should be put on higher attention later on. Due to limited computational capabilities of NAEA certain analyses were also performed by the NCBJ experts [1, 10].

Information from two official IAEA documents (INSAG-25 and TECDOC-1436), describing the principles of risk informed regulations of nuclear facilities as well as the basic framework for IRIDM, were used as a basis for this study [12, 13].

Finally, all these experiences and information were used in further stage of IRIDM, by means of preparation of inputs for decision making process and assignation the input weights. The inputs were set into the following categories: deterministic aspects, probabilistic aspects, mandatory requirements, cost and benefits, organizational influence and doses for workers. Then the importance weights have been assigned to each input category (Tab. 2). The weights were ranging from 0 – negligible impact to 10 – the highest impact on decision.

The highest weight (10) was given to deterministic aspects. This choice comes from the fact that during the operation of reactor, it is necessary to maintain safety limits and requirements of defence in depth methodology.

Since the LEU fuel will be used here simultaneously with HEU fuel and their relative proportion will change in time during whole conversion period, there is a need for analysis of facility behaviour under such condition. This analysis should cover all possible accident scenarios.

Probabilistic aspects should stay in conjunction with the deterministic results. Besides, since this transient period implies a rise of the core damage frequency, the probabilistic aspects should be assigned at least medium weight (8).

Another thing is the mandatory requirements, i.e. all of the conversion-related analyses and in turn all changes performed in the core structure should strictly follow national and international law and regulations. Due to the fact that they can limit some of the actions, their impact should be considered in general at a medium level. However, taking into account that the reactor facility is operated by experienced staff, which follows high standards, it is unlikely to exceed safety limits. For that reason, the low rank (3) was set to mandatory requirements in this study.

Other issues like economic cost and benefits are still quite relevant, because operation of the reactor is highly related to production of radioisotopes for the international market. Thus the medium impact (5) to this IRIDM study was applied.

Reactor core conversion requires also special organizational effort, changes in safety management and competences, leadership or communication pathways between co-workers. This, in turn, means medium impact (5) on final decision.

Since it is highly unlikely to exceed accounted safety limits, radiation doses for workers are of negligible level. That is why their effects are omitted in this study.

Table 2. Weights of the input categories taken into account in the IRIDM process

Category No. (j)	Inputs description	Weight (w_j)
1	Deterministic aspects – safety margins	10
2	Probabilistic aspects – risk changes	8
3	Other – economic costs and benefits	5
4	Other – organizational impact	5
5	Mandatory requirements	3

Next step is to determine an impact of implementation of the various IRIDM options on each particular input. Usually, at the beginning of this process qualitative impact assessment is performed. It means that each option i needs to be analyzed in the context whether it has an overall positive or negative impact on each particular input j. After that the score can be assigned for each option in the range of values from -10 (the highest negative impact) through 0 (no impact) up to 10 (the highest positive impact). It allows evaluating of option i by the total weighted score (S_i) described by the following equation:

$$S_i = \sum_j w_j \cdot s_{ij} \, , \tag{1}$$

where w_j is the weighting factor of the input j and s_{ij} is the impact of option i on the input j [2]. Consequently, the preliminary set of options has been ranked by the S_i factor (Tab. 3).

Table 3. Ranking of the preliminary set of options

Inputs	Option 1		Option 2		Option 3	
	Score (s_{1j})	Weighted score	Score (s_{2j})	Weighted score	Score (s_{3j})	Weighted score
Deterministic	-6	-60	-2	-20	0	0
Probabilistic	-3	-24	-1	-8	0	0
Economic	0	0	-2	-10	-10	-50
Organizational	0	0	-2	-10	-10	-50
Requirements	0	0	-3	-9	0	0
Total (S_i)	---	-84	---	-57	---	-100

Option 1 (full conversion without changes in cooling system) is the best solution from the economic point of view. The radioisotopes can be produced continuously and no additional changes in the organizational system are needed. However, this option has an overall negative impact on both DSA and PSA results, -6 and -3 respectively. This is because the primary cooling channel pumps are not efficient enough to provide appropriate mass flow after conversion. Consequently, the safety margins cannot be maintained, which also increases the probability of an undesired event. Therefore, this option was rejected due to the highest negative impact on the safety aspects.

Option 3 is the best solution in terms of safety. Replacement of the pumps ensures the same operational parameters like these before the core conversion. Thus the results of DSA and PSA would not be changed in this case. However, this option assumes a long-term shutdown of the reactor for the time of pump replacement. This generates, however, significant economic losses associated with interruption of the isotopes production during shutdown. Additionally, it needs some changes in the organizational system at the time of that process. These are the main reasons why option 3 was rejected as well.

Finally, option 2 has been chosen even though there is a slightly negative impact on both safety and economic aspects. Moreover, the additional requirements meaning criteria on power limits have been proposed by the NAEA, which implies necessity of some organizational changes. Due to the power limits a slightly lower production of isotopes is expected. However, the economic losses are not as high as in option 3. Thus the option 2 is much safer than the first one and still very economically attractive. This is also the most balanced solution in the terms of risk distribution between different IRIDM inputs.

5. Conclusions

In this study each IRIDM option has an overall negative impact on the IRIDM inputs. Thus the lowest one, corresponding to the second option, was chosen. However, one has to remember that the decision on core conversion has been made in order to increase the security level, which balances the negative impact on the considered inputs. Thus, the selected option is the most satisfactory one. It assumes that the permission may be granted for partial core conversion before change of the pumps, but with some additional criteria, i.e. to set lower limits on power generated in fuel elements, where it cannot be provided nominal flow. That conclusion stays in compliance with results of the traditional decision making process, meaning the deterministic approach with engineering judgment. It may be also useful for further NAEA considerations, despite that the application of IRIDM is not yet obligatory in Poland.

Acknowledgements

The presented work was supported by the EU and MSHE grant nr POIG.02.03.00-00-013/09.

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otrzymano/received: 15.04.2013 *przyjęto do druku/accepted: 22.04.2013*