ECONOMIC EVALUATION OF A MOBILE NUCLEAR POWER PLANT USING URANIUM OVER 5% ENRICHMENT

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Abstract. Moble nuclear power plants seem to be an interesting alternative to provide electric energy to isolated regions because the conventional electric network cannot reach isolated cities, islands, offshore and merchant ships. These reactors would be built over a floating barge that could go to client's place. This new concept brings up new maintenance and operation issues, especially about autonomy and availability. This study evaluates economic advantages and limitations of using over 5% enrichment fuel on a mobile nuclear power plant (NPP). A supposed mobile NPP is taken as an example and used as calculation basis. An enrichment over 5% could better adjust the maintenance event periods, improving the plant availability, reducing operation costs and improving the competitiveness of this plant type. In addition to the high costs of the enrichment process, the fuel burnup limits and the maintenance activities restrict high levels of fuel enrichment. Therefore, this work suggests a fuel enrichment condition capable to conciliate both cost and performance for a supposed mobile NPP.

1. INTRODUCTION

Mobile nuclear power plants seem to be an interesting alternative to provide electric energy to regions where the conventional electric network cannot reach such as isolated cities, islands, platforms or forest regions. These reactors would be built on a barge that could transport them to the required place to operate. Nuclear power is a proven technology for naval propulsion, with a history of about 700 nuclear naval reactors worldwide [1] however it has not been explored at the same way in the mobile nuclear power plant condition. This mobile condition is supposed to be challenging because it should conciliate a small size nuclear reactor, a lean structure, security operation and low costs.

Mobile conditions require especial design to improve its performance. It must reduce plant stopping period and conciliate reactor and the barge maintenance events. To achieve better performance conditions, this plant should have a long-life core to last until the required maintenance intervals. A conventional barge, normally, performs a 60 months interval between major maintenance events [2], these interventions are specially dedicated to core vessel inspection and ship hull repairs. The challenge is to find a core design that could operate during all this maintenance interval period without refueling and deal with size limitations of a mobile nuclear power plant.

Mobile Nuclear Power Plants demand long core cycle length to avoid maintenance events in short time intervals. Studies about long cycle cores [3], [4] shows that a conventional single-batch core loaded with fuel enriched to 5%w U-235 can achieve a 36 calendar months cycle, at 87% capacity factor, and burn the fuel to about 37.5 MWd/kgU. McMahon [4] has proposed a single-batch reload PWR with fuel enrichment of 7%w U-235 to achieve 38.8 Effective Full Power Months (EFPM) or 44.6 calendar months when operating at a capacity factor of 87%. The reactivity behavior of this 7%w U-235 enrichment fuel core against the number of burnable absorber pins is shown in Figure 1.

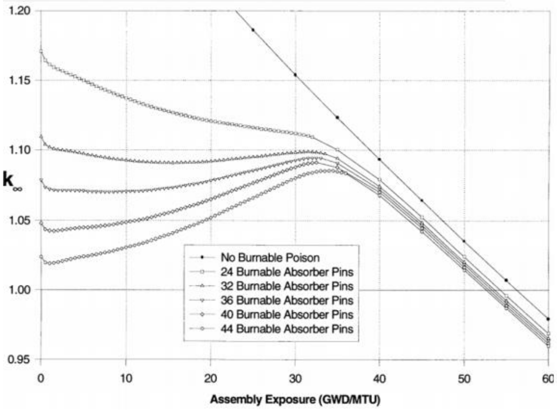


Fig.1 Reactivity behaviour of 7 wt.% U-235 enrichment fuel core [4]

Therefore, an over 5% enrichment fuel could be a solution for this issue. It would increase the core life without increasing the core size. The purpose of this work is to evaluate the costs of enrichment compared to the unavailability cost reduction.

2. METHOD

A prototype mobile nuclear power plant proposed by Freire and Andrade [5] was used as reference for the development of this work, Figure 2 presents the suggested arrangement for the mobile NPP. Note the large quantity of fuel oil to keep the client ship with a safe supply for 14 days.

This work assumes that the nuclear power plant would use a PWR reactor because it is the most successful design up to now due a good synergy between safety, compactness, weight and simplicity

[5]. Compactness and lightweight are important to give room to useful payload. With the advent of passive safety devices, PWR plants achieve safety levels far greater than older designs and construction and the reduction of active (energy powered) devices has reduced maintenance costs.

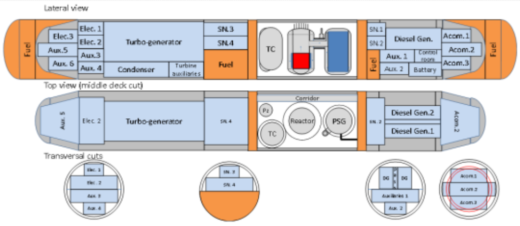


Fig.2 Mobile nuclear power plant proposed arrangement [5]

A mobile nuclear power plant can adopt different strategies for fuel change and core vessel maintenance. One possibility is to bring all needed resources (equipment and personal) to the operating place and perform the maintenance event there. The issue at this condition is that this kind of reactor will normally operate in a far distant place with scarce resources. Other possible strategy is to bring the mobile plant to an adequate place, with all needed resources available to perform the maintenance, which leads to another issue, related to increasing the unavailable time due to displacement. It is possible to consider a fleet of mobile plants with a spare plant unit to replace each other when the maintenance time is reached. In this work will be considered that the best cost benefit relation is reached transferring the mobile plant for a specific maintenance place.

Comparing different sizes of nuclear reactors [6], it is possible to see that smaller size reactors (IAEA defines as “small” those reactors with power <300 MWe and “medium” with <700 MWe) are the logical choice for smaller countries or those with a limited electrical grid. In fact, smaller reactors are now in different stages of development throughout the world and interest in their deployment has been expressed as well. Small reactors have attractive characteristics of simplicity, enhanced safety and require limited financial resources. According to Ragheb [7], a small nuclear power plant that has a 250 MWe is enough to power a million homes.

There are not many reprocess or enrichment facilities operating in nations with advanced nuclear power generation technology. Therefore, the data related to the nuclear fuel cycle cost are mostly estimated costs instead of real costs [8]. It is very difficult to obtain the relevant costs. The nuclear fuel cycle cost has an estimated cost and is inevitably subject to uncertainty [9]. Some studies show that nuclear fuel cycle cost implies in 15–25% of the total cost of nuclear generation [10]. Studies by MIT [11] give an estimated levelized cost of US$84/MWh for nuclear power plants.

3. RESULTS AND DISCUSSION

It is important to estimate the enrichment influence on the plant cost to evaluate the economic viability of using another level of enrichment in the nuclear fuel. The software used to analyze the fuel cost for different enrichment conditions was the “Nuclear Fuel Cost Calculator” from wise-uranium.org. This calculator performs calculus of the nominal and hidden costs of nuclear fuel [12]. It uses the following assumptions: the uranium is purchased on the market, and it is enriched for use in light water reactors, such as pressurized water reactors (PWR) or boiling water reactors (BWR). The reactor fuel is produced from this natural uranium, no MOX is used. The spent fuel is conditioned and disposed of in a final repository and no reprocessing is used.

Calculation was done for generic power plants in different fuel enrichment conditions. Figure 3 presents the behavior of fuel costs for uranium enrichments from 5 to 20% on plants power from 50 to 250 MWe.

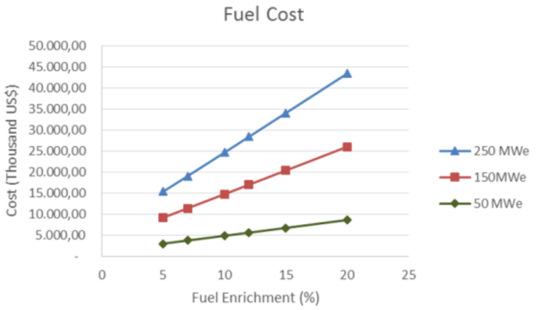


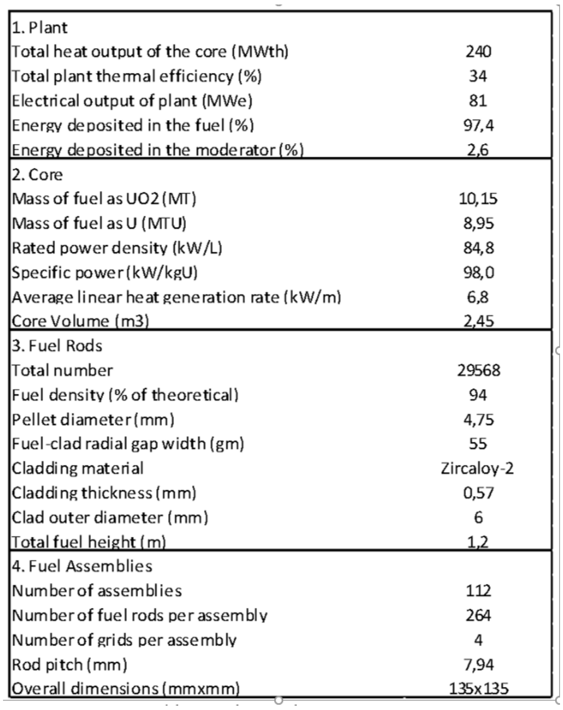
Fig.3 Nuclear fuel cost vs. Enrichment

This study considered a 240MWth mobile nuclear power plant over a 60 months maintenance interval barge, placed in a remote location where the best maintenance strategy is to move the mobile plant to an adequate place that increases in 20 days the unavailable time due to displacement. It was considered that all other costs (plant building, operating, maintenance, etc.) besides the nuclear fuel cost and changing fuel period would still the same in all analyzed conditions. Reprocessing spent fuel was not considered in this evaluation and direct final disposal cost was included in the fuel cost.

The data information used to exemplify the proceeding method to perform this economic evaluation is an estimate. Each mobile nuclear power plant will have its own specific power cost, its barge maintenance needs and costs and each core will have its own fuel cost and cycle length. The main objective of this work is the importance of bringing up the issues that should be treated to achieve better economic performance on this kind of plant condition.

Using a unit cell model, it was possible to estimate the burnup cycle length for the proposed core. HAMMER-TECHNION code was used to simulate the core burnup conditions, the plant and core parameters employed on this evaluation are given in Table 1.

TABLE 1. PLANT AND CORE PARAMETERS



1. Plant	
Total heat output of the core (MWth)	240
Total plant thermal efficiency (%)	34
Electrical output of plant (MWe)	81
Energy deposited in the fuel (%)	97,4
Energy deposited in the moderator (%)	2,6
2. Core	
Mass of fuel as UO2 (MT)	10,15
Mass of fuel as U (MTU)	8,95
Rated power density (kW/L)	84,8
Specific power (kW/kgU)	98,0
Average linear heat generation rate (kW/m)	6,8
Core Volume (m3)	2,45
3. Fuel Rods	
Total number	29568
Fuel density (% of theoretical)	94
Pellet diameter (mm)	4,75
Fuel-clad radial gap width (gm)	55
Cladding material	Zircaloy-2
Cladding thickness (mm)	0,57
Clad outer diameter (mm)	6
Total fuel height (m)	1,2
4. Fuel Assemblies	
Number of assemblies	112
Number of fuel rods per assembly	264
Number of grids per assembly	4
Rod pitch (mm)	7,94
Overall dimensions (mmxmm)	135x135

The simulation output was the behavior of the infinite multiplication factor (k∞) as a result of assembly exposure. Considering that the PWR modeled in this study has a nominal burnup rate of 26.8 MWD/MTU per Effective Full Power Year (EFPD), or 9,8 GWD/MTU per Effective Full Power Year (EFPY), it is possible to estimate the behavior of the infinite multiplication factor (k∞) versus the core operating time. In Figure 4, it is possible to see that a fuel enrichment between 8 and 10% would be necessary to reach the 60 months cycle period.

Considering the 20 unavailable days due to displacement in addition to the fuel cost and the estimated changing fuel event cost, it is possible to build a graphic of different event costs according to the fuel enrichment (Figure 5).

However, one cannot consider a direct comparison of the event costs because different fuel enrichment would provide different core life. For this comparison, it was considered the burnup cycle length obtained in the core simulation, a single-batch reload PWR with fuel enrichment of 5%w U-235 achieves 29,6 calendar months cycle, a 7,5%w U-235 achieves 47,1 calendar months, a 10%w and a 12,5%w U-235 would achieve 64,6 and 82,1 calendar months cycles, respectively. Figure 6 gives a reference of the behavior of the annual cost of changing fuel events for distinct fuel enrichment conditions. To achieve the best performance condition to this system it is necessary to deal with both costs, fuel supplying and fuel change events. It is important to consider that the ship maintenance needs as a limit condition, in this case, a 60 months limit was established for the barge used. For graphic illustration, the 9%w U-235 fuel was used to represent a 60 months autonomy fuel.

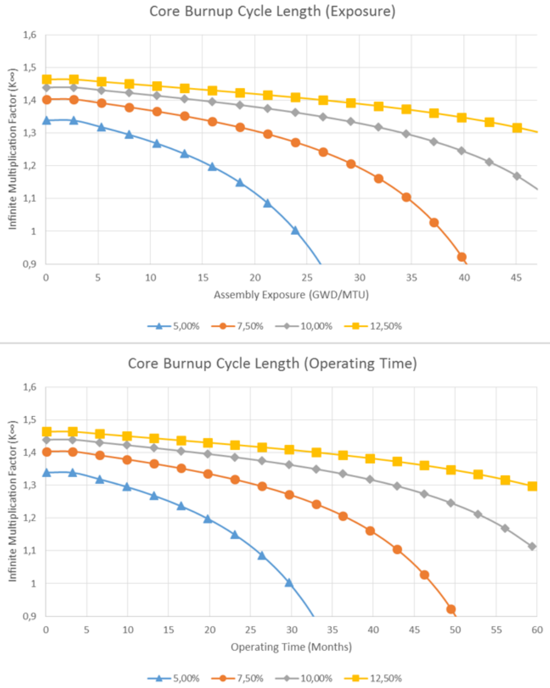


Fig.4 Core burnup cycle length

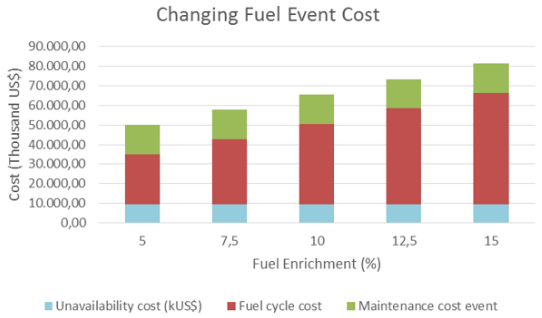


Fig.5 Estimated changing fuel event cost

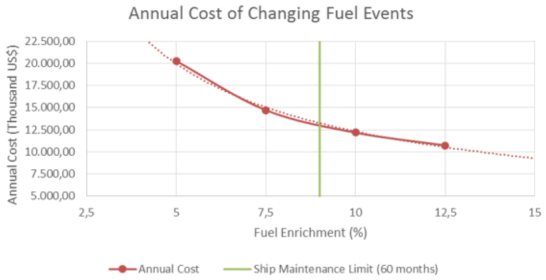


Fig.6 Annual cost of changing fuel events

A fuel enrichment between 8 and 10% U-235 could achieve the best performance considering a 60 months ship maintenance limit. An over 10% U-235 enrichment could provide a better cost, but its use depends on ship and core maintenance developments, higher quality components and reliability improvements.

Another opportunity to reduce costs and improve economic viability is to find alternatives to deal with waste management costs. Depending on the configuration, this cost can represent from 30 to 45% of the total fuel cycle cost. Effective practices on this issue can achieve representative economic results. Figure 7 shows the values that waste management costs can reach.

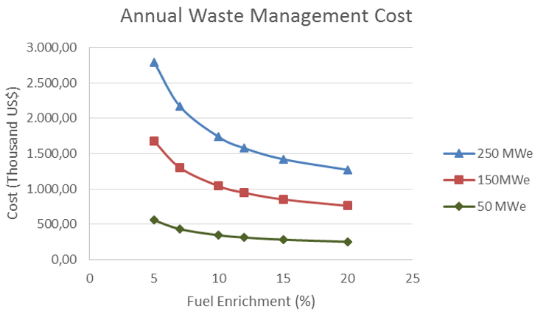


Fig.7 Waste management cost

4. CONCLUSION

Mobile nuclear power plants are an interesting alternative to supply electric power to remote areas. Over 5% U-235 fuel enrichment can improve the economic performance of this kind of nuclear plant, a fuel enrichment between 8 to 10% U-235 was achieved as an ideal condition for a specific situation proposed as study of case. The limiting condition to go further on the enrichment rates is the maintenance conditions for the ship and the core. An extension of maintenance interval periods should be carefully evaluated when dealing with nuclear power units, however it should be explored. Waste management costs also have influences on the fuel cycle cost and seems to be an opportunity to improve the plant costs.

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