TEST IRRADIATION OF RECYCLED URANIUM IN CHINESE CANDU REACTORS

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ABSTRACT

This paper presents the feasibility of using recycled uranium (RU) from Pressurized Water Reactors' (PWR) spent fuel as fuel in Heavy Water CANDU reactors. Together in a four-party partnership, TQNPC, NPIC, CNNFC and AECL have put together a technical case for inserting twenty-four natural uranium equivalent (NUE) bundles into a Chinese Qinshan CANDU reactor for a test irradiation. NUE is a combination of RU and depleted uranium (DU) in such a manner that the NUE fuel will perform identically to natural uranium (NU) fuel.

1. BACKGROUND

With a revival of global nuclear energy, many countries, including China, are seeking to expand the use of economical, carbon-free nuclear energy to meet growing electricity demand and manage global climate change, which ensuring the security of fuel supplies.

In China, "Medium and Long Term National Development Plan (2005-2020) for the Nuclear Power" was published in 2007. According to the plan, by Year 2020, the installed capacity of nuclear power will reach 40 GW and the capacity of the units under construction shall be kept at around 18 GW. Based on current international practices, on the average one 1,000 MW class nuclear power plant consumes about 190 t of the NU per year. By Year 2020, about 10,340 t NU will be needed per year and the accumulated demand on NU will be about 91,364 t in China.

As outlined in Reference [1], China has a large quantity of potential NU resources, but at the present, the degree of mining exploration is low and the identified resources are limited. China not only needs to secure fuel supply through different ways of uranium resources development, but it also plans to invest in advanced research and development projects that deal with improving utilization of NU resources, developing fast reactor technologies to breed fissile materials, developing thorium reactor technologies and thorium-based fuel and developing fusion reactors.

Using RU in existing nuclear power reactors may help to improve the utilization of NU resources. According to European and Japanese experiences, re-enriched RU fuel had a higher radioactivity level and much higher fuel cost than NU fuel. Therefore few countries and PWR station owners are inclined to using RU based re-enriched fuel, and to date, about 75,250 t RU has been reprocessed and stored without any additional use. China's policy is to develop the technology for a closed fuel cycles, so in the future it will produce a large amount of RU. Therefore, it is important to push forward efforts towards research on RU utilization with plans for large-scale implementation.

China is one of the few countries in the world that has both PWR and CANDU technologies. CANDU reactors have excellent neutron economies, making them highly flexible for alternative fuels, and they also have remarkable advantages use of RU. On January 11, 2008, NPIC and AECL signed a memorandum of understanding on advanced reactor technology including low uranium consumption fuel cycle technologies. On November 3, 2008, the four parties, namely TQNPC, NPIC, CNNFC and AECL signed the agreement to cooperate on advanced CANDU fuel development and demonstration. A joint working group has been set up for the demonstration project of using RU fuel in Qinshan Phase III reactor (RUQ3) and plans to take about 4 years to complete the project.

2. THE STATUS OF REPROCESSING TECHNOLOGY IN THE WORLD

The use of RU has a worldwide history of more than thirty years. According to an International Atomic Energy Agency (IAEA) statistic, RU has been used in 41 reactors in various countries, for example, France, the United Kingdom, Russia and India. The reactor types involved include PWR, HWR, BWR, RBMK and AGR, as outlined in Reference [2].

In France, Electrique de France (EDF) and the main French fuel cycle companies started the research from 1984 and the experiments from 1985 to verify whether RU can be used at industrial scale. Since 1997, between 150 and 400 t RU has been recycled in Cruas-3 and Cruas-4 each year. Until Dec. 2003, France had recycled about 2,900 t RU, but converted 6,700 t RU into stable compounds stored for future use.

In the United Kingdom, all the spent fuels discharged from Magnox reactors have been reprocessed. Of all these, 1,600 t were re-enriched in order to manufacture AGR fuels. By the mid 1990s, about 60% of AGR fuels were made from spent fuels of Magnox reactors. However, this was discontinued in 1996 because of relatively poor economic performances.

India has a relatively poor supply of uranium resources, yet it is abundant with thorium resources. Therefore, India has adopted a closed fuel cycle strategy. RU reprocessed from CANDU spent fuels has been used in initial CANDU reactor cores to flatten neutron flux distribution. In 2003, about 1,600 t of RU were used in the initial reactor core of MAPS-2, after pressure tube replacements.

As outlined in Reference [3], in the 1990s, AECL, KAERI and other companies began research and test projects on the direct use of RU in CANDU. . AECL cooperated with COGEMA and BNFP to produce RU powder using thermal de-nitration and ADU route, and the finished RU powder and finished pellets met all the physical and chemical specifications for CANDU fuel. The radioactive dose rates in the fuel manufacturing processes satisfied the dose limit requirements.

Overall, there were no major technical issues with RU utilization. Even though there are many years of RU experience in various countries, RU fuels have not been in wide use due to low economic incentives and political reasons. . However, in recent years, the significant rise of the price of uranium resources and the fast development of global nuclear power generation have driven a number of research institutions and owners to reconsider RU utilization. In February 2006, the Department of Energy (DOE) of the United States proposed the Global Nuclear Energy

Partnership (GNEP), which has greatly influenced worldwide research in RU reuse, and has considered CANDU reactors paramount to this vision.

3. TECHNICAL OPTIONS FOR RU USED IN CANDU REACTORS

CANDU reactors have excellent neutron economy, and as a result they can effectively utilize a number of different fuels, such as natural uranium, low enriched uranium, RU, MOX, and thorium. Based on the fuel cycle data shown in Table 1, a comparison between PWR and CANDU once-through uranium consumption and utilization is shown in Table 2. Table 2 shows that utilization of RU in CANDU can improve natural uranium consumption rate by 23%, and reduce spent fuel by about 30%.

Table 1: Fuel Cycle Data

Fuel Cycle Option	U-235 content (wt. %)	Burnup (MWd/kg HE)	Net Thermal Efficiency (%)
PWR with ENU[1]	3.7	40	35
CANDU with NU	0.711	7.5	34
CANDU with 0.9% LEU[2]	0.9	14	34
PWR/CANDU, with RU in CANDU	0.9	13	34

Table 2: Uranium Consumption and Utilization Data

Fuel cycle option	NU Consumption (Mg U/GW_e a)	Equivalent NU Burnup (MW_{th}d / kg U)	Spent Fuel Arising (Mg HE/ GW_e a)
PWR with ENU	195	5.3	26
CANDU with NU	143 (- 26%)	7.5	143
CANDU with 0.9% LEU	114 (-41%)	9.5	77
PWR/CANDU, with RU Direct Use in CANDU	150 (-23%)	7.0	20

Subsequently, China is planning to take two steps to develop RU fuel for its CANDU fleet. The first step is to combine RU and DU in a 37-element bundle in such a manner that the combined fuel will perform identically to NU fuel. The RU and DU with different fissile content can be blended in various ratios to ensure that the final product closely resembling NU fuel and the subsequent NUE fuel shall have minimal reactor safety and licensing barriers for deployment in CANDU reactors, and have minimal investment, and can be implemented soon.

The second step is to use RU directly in CANDU with the advanced CANFLEX fuel as the fuel carrier. In this scenario, the RU contains 0.9% -1.2% U-235. It has better uranium resource utilization, and more additional energy production with very minor increase in spent fuel waste

[1] Enriched Natural Uranium
[2] Low Enrichment Uranium

volume.

4. FEASIBILITY STUDY OF USING NUE AS CANDU FUEL IN CHINA

4.1 RU AND DU RESOURCE

Currently, China has 11 operating nuclear power plants and 8 units on construction, the majority of which are PWR technologies. The U-235 content in PWR fresh fuel is between 3.2% and 5.0%, and U-235 content in PWR spent fuel is between 0.8% and 1.2%. DU is the tails produced during enrichment of NU and is easily accessible from China's fuel enrichment plant. At the present, China does not have any supply of RU resources for this test irradiation, is procuring it from other countries. However, China's nuclear fuel strategy envisages large scale reprocessing, driven by the requirement to create inventory for plutonium start-up fuels for a planned fast breeder reactor fleet as well as to assist in managing spent fuel. China National Nuclear Corporation (CNNC) is currently in the construction phase of building a pilot reprocessing facility, which is expected to have the capacity to process about 100 tonnes/y of spent fuel.

4.2 NUE FUEL RADIOACTIVITY

RU fuel radioactivity is an important consideration for its utilization, because of the increased safety requirements and higher associated costs. Increased radioactivity has a greater effect on PWR because there are more processing steps associated with manufacturing fuel (conversion and re-enrichment). Furthermore, since RU has to be enriched for use in a PWR, re-enriching it also increases the concentration of U-232, which is the dominant source of the radioactivity. U-232 itself is not considered a radiological hazard, however its subsequent decay products are high-energy gamma emitters. The build-up of radioactivity of U-232 increases with time and therefore, the sooner the fuel can be fabricated and inserted into the reactor, the fewer handling/radioactivity concerns that arise. Again, since CANDU fuel does not require as many processing steps, it limits the time for U-232 decay.

According to radiation dose modeling and AECL experiments, the radioactivity of RU after 2 years of reprocessing is roughly 2-3 times that of NU. This increased level is still within acceptable radiation protection standards and it is not envisaged that any major procedural changes would be required during the test irradiation.

4.3 REACTOR PHYSICS ASSESSMENT

Equivalence of NU and NUE fuel is assessed by reactor physics calculations. The WIMS computer code is used in AECL's assessment. Figure 1 shows the change of lattice k-inf of NU and NUE fuel with the burnup history. RU in three cases has different U-235 content and reprocessed from different batches of spent fuel, the spent fuel in case 3 with 3.2% initial concentration and 33000MWd/tU burnup, the spent fuel in case 4 with 4.45% initial concentration and 45000MWd/tU burnup, then spent fuel in case 5 from TVEL Corporation. As shown in figure 1, their reactivity is almost the same and so can be considered as equivalent to NU.

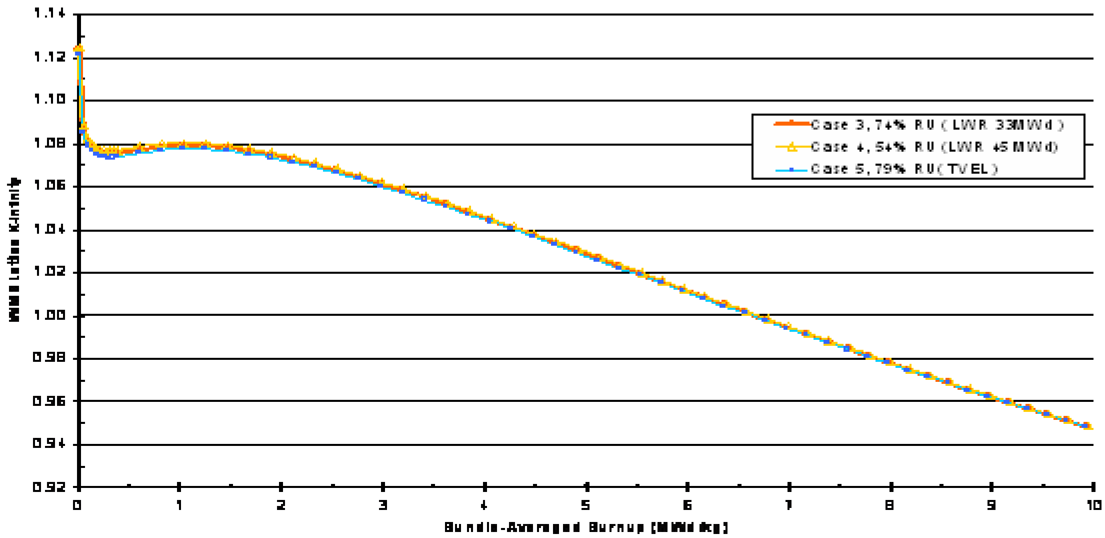

Figure 1. Fuel K-inf versus bundle-averaged burnup history

Figure 2 Shows coolant void reactivity. As seen from figure 2, the 3 types of RU fuel are almost equivalent to NU. Moreover, investigate RU effect on the potion of delay neutron (DN), the result shows that there are no significant effects on the portion of the delayed neutron.

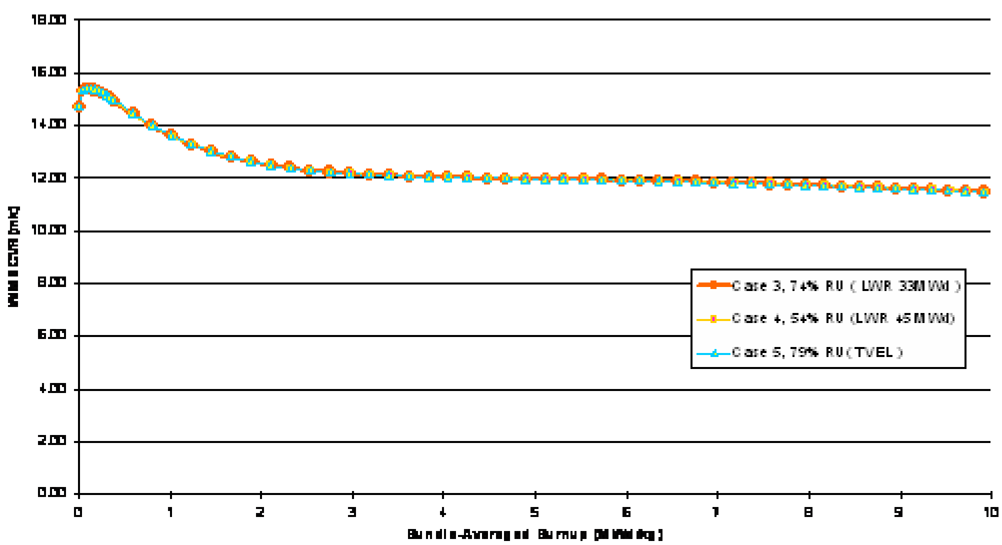

Figure 2. CVR versus bundle-averaged burnup history

4.4 ACCESSMENT OF NUE FUEL FABRICATION, TRANSPORTATION AND OPERATION

CANDU fuel is processed at the CNNFC facility. The current fuel manufacturing process can be easily modified to make 37-element NUE fuel bundles. The dose exposure for manufacturing and maintenance staff members engaged in the preparation of UO_2 pellets is still less than 15 mSv/a and the dose exposure for operators working in the fuel bundle assembling areas is within

1 mSv/a, which meets regulatory requirements. Because the RU and DU is mixed to achieve a U-235 concentration close to 0.71 wt. %, there are no specific requirements for NUE fuel bundle during transportation, storage, and operation.

5. RUQ3 PROJECT WORK PLAN AND PROGRESS

The RUQ3 working group is putting together a technical and business case to demonstrate that CANDU reactors can efficiently burn RU within the safety-licensing envelope. The work scope includes NUE fuel conceptual design, safety assessments, physics calculations, fuel manufacturing design modifications, RU fuel purchasing, prototype and actual NUE fuel pellet and bundle manufacturing, National Nuclear Safety Agency (NNSA) review and test irradiation of NUE fuel bundles in Qinshan CANDU reactor. The project milestones are scheduled as the follows.

1) To complete a feasibility study by November 2008;
2) To complete conceptual design by May 2009;
3) To confirm and accept mixing technology and pellet manufacture by September 2009;
4) To gain approval from NNSA by the end of 2009;
5) To begin test irradiation by early 2010 and remove bundles for in-bay inspection by the end of 2011.

The feasibility study and the majority of the conceptual design have been completed. At present, the remaining design work, RU procurement and mixing methodology study is underway.

6. CONCLUSIONS

RU implementation in CANDU reactors will play an important part of China's closed fuel cycle system, which will ultimately improve the sustainability of fuel resources. The blended combination of RU and DU as NUE fuel in a CANDU reactor is technically feasible. It is the simplest and quickest path to efficiently utilize alternative fuel sources in proven CANDU reactors but in the future direct use of RU in CANDU will allow for better uranium resource utilization, more additional energy production, and very minor increase in spent fuel waste volume.

As a four-party partnership, TQNPC, NPIC, CNNFC and AECL are combining expertise and knowledge to make RU utilization in a CANDU a reality in China. NUE fuel implementation is considered a short-term target, and will create the framework for future fuel projects.

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