SAFETY ASSESSMENT TO SUPPORT NUE FUEL FULL CORE IMPLEMENTATION IN CANDU REACTORS

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ABSTRACT – The Natural Uranium Equivalent (NUE) fuel contains a combination of recycled uranium and depleted uranium, in such a manner that the resulting mixture is similar to the natural uranium currently used in CANDU® reactors. Based on successful preliminary results of 24 bundles of NUE fuel demonstration irradiation in Qinshan CANDU 6 Unit 1, the NUE full core implementation program has been developed in cooperation with the Third Qinshan Nuclear Power Company and Candu Energy Inc, which has recently received Chinese government policy and funding support from their National-Level Energy Innovation program. This paper presents the safety assessment results to technically support NUE fuel full core implementation in CANDU reactors.

1. Introduction

CANDU reactors have a unique fuel cycle capability that enables them to utilize alternative fuel options. Since 2008, Candu Energy Inc. (Candu) in partnership with China National Nuclear Corporation's (CNNC), Third Qinshan Nuclear Power Corporation (TQNPC), China North Nuclear Fuel Company (CNNFC) and the Nuclear Power Institute of China (NPIC), have developed a 'first-of-its-kind' NUE fuel to implement alternative fuel cycles into CANDU reactors which use recycled and depleted uranium based fuels [1]. NUE fuel contains a combination of recycled uranium (RU) and depleted uranium (DU) that simulates natural uranium (NU) behaviour. NUE bundle geometry and materials remain the same as the current NU bundle (as shown in Figure 1).

The NUE program has successfully completed the development, design, and fabrication, as well as a demonstration irradiation in Qinshan Unit 1. With the completion of the formal design review stage in May 2013, the NUE program for full core implementation and licensing will culminate in the conversion of both Qinshan CANDU units to NUE fuel in 2014 [1]. The use of RU reduces the overall environmental impact of the entire fuel cycle by improving the efficiency of natural resource management and reducing radioactive waste by reducing RU and DU stockpiles. This fuel cycle program has recently received Chinese government policy and funding support from their National-Level Energy Innovation program.

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As part of the NUE program, an initial safety assessment concluded there are no safety concerns or adverse implications of replacing NU fuel with NUE fuel for the two-channel demonstration irradiation [2]. This in reactor demonstration irradiation of the 24 NUE fuel bundles in two channels was successfully completed in Qinshan CANDU Unit 1 in March 2011 [1][3]. During the demonstration irradiation, the normal operation of the plant was not affected by the use of NUE fuel in two channels. The NUE fuel bundles were inserted into the reactor core without any abnormal monitor indicators. At the end of the refuelling cycle and after a period of time for cooling, the irradiated bundles underwent a thorough in-bay inspection to visually examine them for any defects or anomalies. The NUE demonstration irradiation bundles were subject to inspection along with reference NU bundles from similar locations for direct comparison. All of the visual evidence, based on the in-bay inspection, supports the conclusion that the NUE fuel bundle performance is the same as that of the NU fuel bundle; there were no notable differences [1][3]. Further confirmation on other performance parameters will be provided through a post irradiation examination.

The project for full core implementation of NUE fuel in Qinshan CANDU reactors was approved by China National Nuclear Corporation (CNNC) in March 2011, with the contract signed between Third Qinshan Nuclear Power Company (TQNPC) and Candu [1][3]. As part of the contract, a safety assessment was performed based on the completed NUE fuel design and specifications, reactor physics analyses, evaluation of the impact of plant systems and equipment, radiation protection, environmental and human factors assessments, all through the application of Candu's quality assurance program. This paper provides an overview of the safety assessment on full core implementation of NUE fuel in CANDU reactors.

Figure 1 CANDU 6 37-Element Fuel Bundle

2. NUE Fuel and Safety Assessment Approach

The basic definition of the NUE fuel that will be used in the full core application, in two aspects, is described as follows:

1) The NUE fuel pellets and elements will have the same geometric dimensions and use the same element and bundle designs as the Qinshan CANDU 6 37-element NU fuel, and

2) With the implementation of a full core of NUE fuel, the operating conditions of the reactor must stay within the Qinshan licensing envelope as set out in the Qinshan CANDU Revised Final Safety Analysis Report (herein referred to as the Safety Report).

Therefore, the NUE bundle geometry and materials remain the same as the current NU bundle (as shown in Figure 1), except for the fuel pellet material which has a slightly different chemical composition. With NUE fuel design and specifications, NUE fuel contains a combination of RU and DU, in such a manner that the resulting mixture is similar to NU fuel currently used in CANDU reactors [1].

With the initial safety assessment and successful two-channel NUE demonstration irradiation [2], the existing safety analyses for NU fuel documented in the Qinshan Safety Report are expected to be insignificantly affected by using NUE fuel in the full core at the Qinshan CANDU reactors. To gain further confidence and to obtain regulatory approval for fuelling NUE fuel in the full core of Qinshan reactors, it is important to demonstrate that adequate safety margins still remain for the operation of NUE full core. Hence, the safety assessment focuses on the impact of using NUE fuel on the existing safety analysis. The approach of the final safety assessment is taken through two steps:

- Assess the safety implication of using NUE fuel and determine the limiting cases for NUE fuel full core safety analysis based on a review of Qinshan Safety Report, and

- Perform safety analysis with these limiting cases.

The overall objective of the safety assessment is to demonstrate that the safety implication of using NUE fuel in the full core is negligible.

3. Potential Safety Implication and Determination of Limiting Cases

3.1 Criteria to Determine Limiting Cases

The basis of the NUE program is to ensure the use of NUE fuel in the Qinshan CANDU reactors has minimal impact on plant operation. The average fuel exit burnup for the reference 37-element NU fuel in the Qinshan CANDU 6 plant is 7,500 MWd/tU. The content of ^{235}U in NUE fuel is slightly higher than the NU fuel to offset additional neutron absorption from the impurities in NUE and to match the exit-burnup. As such, the reactivity of NUE fuel is higher than NU fuel when the fuel is loaded into the core but it gradually decreases until the end of the fuel life where the reactivity is lower than that of NU fuel. This reactivity difference between irradiated NUE and NU fuels can be reflected by reactor engineering design and optimizing parameter, k-infinity, as shown in Figure 2. It is worthwhile to point out that the degree of extra enrichment required for the NUE fuel used in CANDU reactors, is much less than what is required when RU is re-enriched for the use in light water reactors, i.e., almost by a factor of 10 or more. Hence, the overall reactivity of NUE fuel is equivalent to the NU fuel as shown in Figure 2.

The difference in reactivity of fresh NUE fuel translates to a higher power early in the irradiation. The maximum difference in bundle and channel powers occurs when the difference in reactivity between the NUE and the reference NU fuel is at its maximum. Such limiting condition occurs after refuelling the reactor with fresh fuel. However, the NUE fuel maximum channel and bundle powers and the maximum channel power ripple remain well below their power limits with sufficient margin. The spatial control performance remains within normal range as well. As shown in Figure 3, there is also no significant relative power change within a fuel bundle for both NU and NUE fuel bundles during their normal irradiation life.

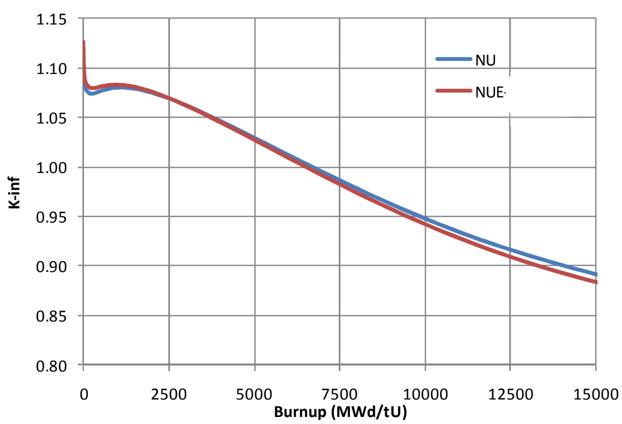

Figure 2 K-infinity Variation as Function of Fuel Bundle Burnup

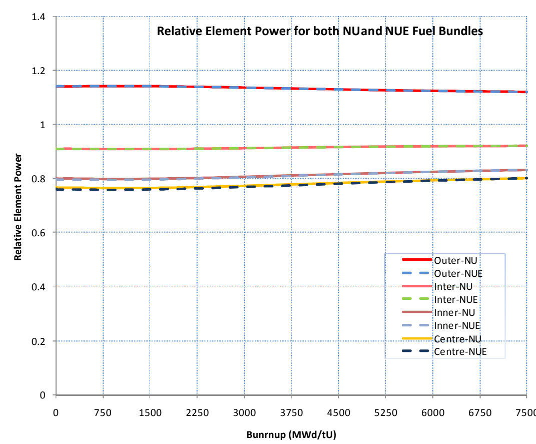

Figure 3 Comparison of Relative Element Power between NU and NUE Fuel Bundles

The differences in reactivity coefficients between NU fuel and NUE fuel may impact the nominal flux distribution and reactivity during accidents, resulting in a difference in power transient following an initiating event. As such, the events could be affected by the different power transient for NUE fuel. The limiting cases are identified based on the reactor power transient during the period prior to reactor shutdown following the events. The following criteria are used to determine the limiting cases for NUE full core safety analysis:

1. The event is considered as a limiting case for further analysis if the safety implication of using NUE fuel in the full core is assessed to be significant for the event. Such limiting cases are analyzed for the NUE fuel in the full core to confirm that the established acceptance criteria (as discussed in Reference [2]) for the Qinshan CANDU Safety Report are not challenged by using NUE fuel in the full core.

2. Even though the safety implication of using NUE fuel in the full core is insignificant, the event is also considered as a limiting case for further analysis if it is judged to be the bounding case for other events in terms of the impact of using NUE fuel on the power transient. The NUE full core analysis for such a limiting case is to show that the impact of NUE fuel on the existing safety analysis is negligible.

The potential impact of NUE fuel on the safety margin is a factor considered for determining the limiting cases for NUE full core analysis. If there is a concern that the safety margin for the event could be affected by NUE fuel, further analysis for the event is considered to demonstrate that the established acceptance criteria are still met by using NUE fuel in the full core. If a large safety margin is demonstrated in the Qinshan CANDU Safety Report for the event, a limiting case for further NUE full core analysis is not necessary, provided that the potential safety implication of using NUE fuel is insignificant.

3.2 Potential Safety Implication of NUE Fuel

The uranium isotope difference between NUE and NU fuel may have potential safety implications for the reactor with an NUE core, which is discussed in the sub-sections below.

3.2.1 Fission Products

The source terms of fission product releases estimated for the dose calculation are based on the equilibrium core. Traceable fission products and actinides contained in the NUE fuel have no impact on the dose calculation. The levels of some impurities unique to fresh NUE fuel, such as fission products and actinides, are reached by NU fuel in a CANDU reactor after irradiation periods ranging from a few minutes to a few days, depending on the particular isotope.

Slightly different uranium isotopes between NUE and NU fuels could result in a slight variation in fission products during fuel irradiation life of NUE fuel. However, the fission product inventory used for the dose calculation in the Qinshan Safety Report for NU core bounds the variation in fission products for NUE fuel. The key factors affecting the fission product inventory are the fuel power and burnup at the time of the accident. The range of linear power and burnup of the fuel elements in a CANDU 6 equilibrium core is wide. In the existing Qinshan safety analysis, the fission product inventory was estimated based on a combination of high power and high burnup, resulting in an upper bound fission product inventory prediction. The limiting power envelope was used in the analysis. The bounding power and burnup for fuel elements in different bundles of the channel at the time of the accident were used for the fission product inventory calculation. As discussed in Section 2, the NUE fuel is essentially equivalent to NU fuel, including the average burnup and safe operating envelope. As such, a slight variation in fission products during fuel irradiation life for NUE fuel is well bounded by the fission product inventory estimated based on bounding power and burnup for NU fuel.

3.2.2 Reactor and Radiation Physics

Based on radiation physics calculations, the traceable fission products and actinides initially contained in the NUE fuel have no impact on the bundle decay power magnitude as shown in

Figure 4. Hence, the core response after the reactor trip is expected to be the same for NU and NUE in terms of the overall heat load.

The increased content of ^{235}U in NUE fuel results in a slight difference in reactivity between NUE fuel and NU fuel. Key reactivity parameters include coolant void reactivity (CVR), fuel temperature reactivity, and moderator temperature. However, the comparison results indicate that the difference in reactivity feedback coefficients between NUE and NU fuels are insignificant.

It is further identified that among these key reactivity parameters, a slightly higher CVR for NUE fuel (as shown in Figure 5) result in a more limiting power transient in some events. However, its effect on the safety analysis in use NUE is expected to be insignificant, since the CVR remains in the same magnitude for both NU and NUE fuels and is a relatively slow reactivity change, which can be effectively supressed by CANDU two independent, redundant, capable, separated, testable, and reliable shutdown systems, in additional to the reactor regulating system. To provide further confidence, confirmation analysis for the limiting cases is part of the NUE program. The effect of the CVR difference on the event is the key element considered for determining the limiting cases to be analysed for NUE fuel in the full core. Therefore, the voiding transient following the event is a key factor for determining the limiting cases.

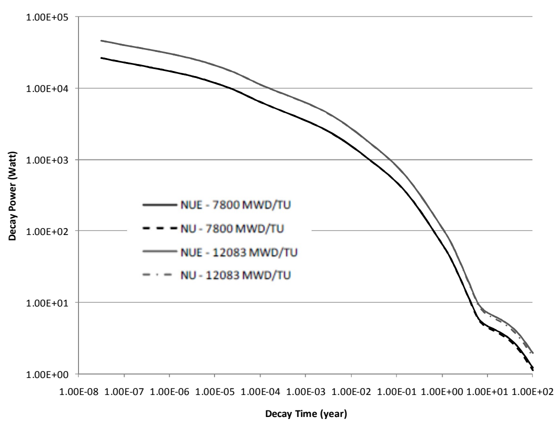

Figure 4 Bundle Decay Power Curves for NU and NUE Fuel

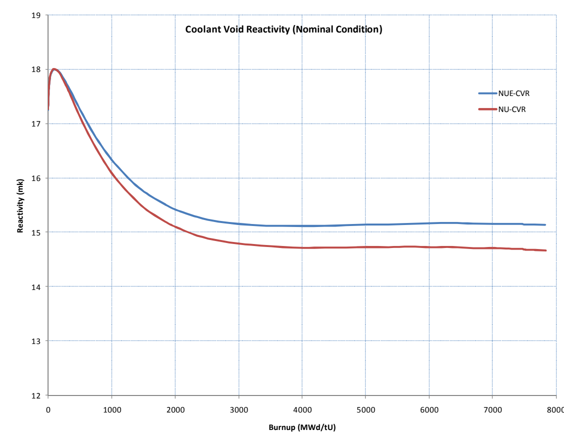

Figure 5 Comparison of Coolant Void Reactivity between NU and NUE Fuel for Postulated Complete Core Voiding

3.2.3 <u>Thermalhydraulics</u>

Because the geometric dimensions and surface materials of the NUE fuel bundle are identical to the NU fuel bundle, the local flow resistance in the fuel channel is the same and the local channel flow conditions are not affected by using NUE fuel. The axial power profile for NUE fuel is similar to the NU fuel. Reactor normal operating conditions are not affected by fuelling NUE fuel in the full core. Prior to accidents, the fuel conditions (e.g., fuel and sheath temperatures and irradiation levels) are not affected by using NUE fuel, since the channel, bundle, as well as element powers using NUE fuel are within the same limiting operating envelopes as NU fuel, as discussed in Section 2. The initial conditions (e.g., coolant pressure, temperature, and density) used for safety analyses are generated from the steady operational state upon the initiation of postulated accident events. Thus the initial conditions used for Qinshan CANDU safety analysis are not affected by using NUE fuel.

Following an accident, the plant thermalhydraulic behaviour for the NUE core is similar to that of the NU core, given that NUE fuel behaves like NU fuel in terms of reactor physics (see Section 3.2.2). However, a slight difference in reactivity feedback coefficient between NUE and NU fuel cause a slight variation in the power transient following an event. This may affect the plant thermalhydraulic behaviour following the event. As such, analysis for the limiting cases is performed to confirm the effect of NUE fuel on the thermalhydraulic transient is insignificant.

3.2.4 Fuel Handling and Storage

The NUE fresh fuel is expected to have a higher external dose rate than the NU fresh fuel. Although the dose rate of NUE fresh fuel is higher than NU fresh fuel, its magnitude is still low enough that permissible occupational dose uptake can be achieved. This can be addressed with additional precautions, including minor changes necessary for operators fulfilling these duties (which includes shielding and procedural modifications), based on the as low as reasonably achievable (ALARA) principle, for fresh fuel fabrication, transportation, and fresh fuel handling.

As shown in Figure 4, the spent NUE fuel decay heat power at short decay times following core discharge is equivalent to NU, and it is only at long decay times (~6 years) that the decay heat is slightly higher with a very small increase. This does not have a significant impact on spent fuel handling and spent fuel storage using NUE fuel. The NUE project has assessed that a uniform minimum cooling time can be used for both NU and NUE to ensure that the bundle decay power is at a level that facilitates spent fuel bundle transfers to dry storage, and that the overall spent fuel bay heat loading and space are within the design capacity. Therefore, there is no further safety concern on fuel handling and storage.

3.2.5 Four Limiting Cases

To assess the effects of NUE fuel on the safety analysis and determine the limiting cases for NUE fuel full core safety analysis, all the analyzed events in the Qinshan Safety Report are reviewed. For each event, the analysis results reported in the Qinshan Safety Report are reviewed to assess the potential effect of using NUE fuel on safety. As discussed in previous sections, the voiding transient following the event is a key factor to be considered to determine the limiting cases. It was concluded that the effect of NUE fuel on the analysis results is negligible and thus the safety implication of using NUE fuel in the full core would be insignificant.

However, to provide confidence, four limiting cases for the NUE core are chosen to be performed to confirm that the impact of using NUE fuel in the full core on the current safety analysis results is negligible. The limiting cases are: large loss-of-coolant accident (LOCA) with 100% pump suction break (large LOCA event), small LOCA with 2.5% reactor inlet header (RIH) break (small LOCA event), loss of forced circulation: single pump trip at high powers (loss of HTS flow event), and a steam and feedwater circuit event: loss of feedwater pumps (loss of feedwater flow event).

Large LOCA Event

Large LOCA is determined as a limiting case to be analysed for NUE fuel in the full core since it bounds all other events in terms of the effect of using NUE fuel on the power transient. It is expected that the effect of using the NUE fuel in the full core on the power pulse would be small. The analysis is to confirm that the power pulse predicted for NU fuel is not changed significantly by fuelling NUE fuel in the full core.

Small LOCA Event

Though no safety concern is expected for the small LOCA event with the NUE core, a confirmatory analysis for NUE core is suggested for small LOCA. A 2.5% RIH break is suggested as a limiting case for NUE fuel full core analysis to determine whether the reactor regulating system (RRS) is effective in maintaining the reactor power at its setpoint, at least until the time of reactor trip on a process trip parameter; otherwise, the trip by the regional overpower protection (ROP) system will be initiated to protect the reactor against overpower when using either NUE or NU fuel.

Loss of forced circulation: Single pump trip at higher powers

Single HTS pump trip is selected as a limiting case for NUE full core analysis to confirm that trip coverage is not affected by NUE fuel. The high neutron power trip alone is not effective for single pump trip from an initial power below 90% FP, while the process trips remain effective. As such, the assessment focuses on the event between 90% FP and 103% FP.

Steam and feedwater circuit event: loss of feedwater pumps

Loss of steam generator feedwater pumps is identified as a limiting case for NUE fuel full core analysis to confirm that trip coverage is not affected by using NUE fuel in the full core. The loss of feedwater pumps is more limiting than other secondary side events in terms of fuel cooling.

4. Analysis of Limiting Cases

4.1 General Analysis Approach and Acceptance Criteria

The detailed analyses have been performed for the identified four limiting cases. In the analysis, the same analysis toolsets and general approach are applied to both NU and NUE cores. This makes the results directly comparable between NU and NUE fuel types. Hence, quantitative assessment of any potential difference of the system response from NU and NUE full cores can effectively be made.

Qinshan CANDU reactors maintain the dual, independent, fast-acting reactor shutdown safety systems, each of a highly reliable, redundant design. Consistent with traditional CANDU practice, the analysis demonstrates that each of two safety shutdown systems, acting independently, is capable of shutting down the reactor and meeting all of the relevant acceptance criteria through analyzing the least effective of the two. Reactor trip is assumed to occur on the second trip signal of the latest shutdown system. In addition, the reactor power transient is analyzed for a wide range of starting power levels up to and including 103% full power applying the limit-of-operating-envelope approach.

Qinshan CANDU 6 reactors were designed by AECL and licensed in China based on Canadian safety requirements and Chinese regulatory requirements. The final safety analysis report for the Qinshan CANDU reactors forms the current licensing basis for the use of NU and NUE fuel. The CNSC requirements reflected in several AECB* regulatory documents, as discussed in Reference [2], are applied in analysis. The reactor power transient during the period prior to reactor shutdown following the events is considered a key factor for assessing the effect of NUE fuel on the event (Section 3). Hence, the related derived acceptance criteria are the limit of fuel enthalpy to avoid the fuel breakup threshold during the overpower phase and the limit of fuel sheath temperature precluding systematic fuel failure for the void generation phase, as considered in the Qinshan CANDU Safety Report.

4.2 Large LOCA Event

The change in the power pulse results due to the partial or full core of NUE fuel is found to be very small, showing no significant difference from the full core of NU fuel results reassessed here and the existing results presented in the Qinshan Safety Report.

The analysis target for the power pulse calculation is met in all analysed cases since the calculated total enthalpy in the hottest fuel element in each case was significantly lower than the limit of fuel breakup threshold for both NU and NUE fuel types. In addition, hot bundle enthalpy is similar to the results reported in the Qinshan Safety Report, meeting the acceptance criterion with sufficient margin. Therefore, for this NUE full core project, the results for the large LOCA analysis show there is no significant impact on the results using NUE fuel in Qinshan CANDU 6 cores.

A sensitivity study case is also performed using the transition core conditions (at the mid-point of the transition to full NUE fuel core (i.e., 250 FPD). The results confirm that a transition core (with mixed NU and NUE fuel bundles present in the core) between a NU full core and NUE full core is bounded by the NUE full core.

4.3 Small LOCA Event

In the overall trip coverage for small LOCA, there is a transition from the process trips to neutronic (e.g., ROP) trips as the break size increases. With the high end break size for the small LOCA assessed here (2.5% RIH break), this transition boundary from process trips to neutronic trips is slightly shifted with NUE. It indicates that the coverage provided by the neutronic trips is expected to be slightly larger, while the trip coverage provided by the process trips remains the same as the use of NU fuel. The overall trip coverage is similar between NU and NUE.

The results for the 2.5% RIH break show that there is no significant impact on the reactor trip time using NUE or NU fuels, while the NUE core has a slightly earlier power trip. Also, within

- The former Atomic Energy Control Board (AECB) was replaced by the Canadian Nuclear Safety Commission (CNSC) in 2000 under the Nuclear Safety and Control Act.

5 seconds of the power trip, the fuel sheath temperatures for both NU and NUE cores remains low (with a large margin below the limit of fuel sheath temperature) in the simulation, crediting the ROP trip for both NU and NUE full cores using the high power single channel model.

The simulation shows that with the effective second trip for small LOCA of 2.5% RIH break, no systematic fuel failure occurs and hence the safety limit is not exceeded with sufficient margin for both NU and NUE full cores.

4.4 Loss of HTS Flow Event

The results for the single pump trip case shows there is no significant impact on the reactor trip time using NUE or NU fuels for both 103% FP and 90% FP. The high power single channel model simulation for 90% FP shows that low sheath temperatures are maintained (with a large margin below the limit of fuel sheath temperature) prior to crediting the backup trip for SDS2 on the delayed HTS high pressure for both NU and NUE full cores. Therefore the simulation for the single pump trip case crediting the backup trip shows that no systematic fuel failures occurred thus the safety limit is not exceeded with sufficient margin.

4.5 Loss of Feedwater Flow Event

The results of the main feedwater pump trip case show that NUE core has a negligible impact on reactor trip time (i.e., the difference in trip times is less than 0.1 second). The high power single channel model simulation shows the sheath temperatures remain low (with a large margin below the limit of fuel sheath temperature) prior to crediting the backup trip on low steam generator level for both NU and NUE full cores. Therefore the simulation for the main feedwater pump trip case at 103% FP when crediting the backup trip shows that no systematic fuel failures occurred thus the safety limit is not exceeded with sufficient margin.

4.6 Overall Results of Safety Analysis on Limiting Cases

The limiting cases for safety analysis of the full core implementation of NUE fuel for the Qinshan CANDU nuclear power plant are performed. The results indicate that the NUE fuelled core has no significant impact on the results of the limiting safety analysis cases, directly compared with the NU fuelled core. For each of the limiting cases, the corresponding acceptance criteria are met and sufficient margin and the safety limits are maintained. Analysis of the most significant limiting case (Large LOCA) for the transition core case (with mixed NU and NUE fuel bundles present in the core) indicates that this conclusion is also valid during the transition period.

Results of these safety limiting cases demonstrate that the differences in the safety implication of loading NUE fuel in the full core is negligible compared with that using NU fuel.

5. Conclusions and CANDU Fuel Cycle Discussions

The project for full core implementation and licensing work that will culminate with the conversion of Qinshan CANDU units to NUE fuel are near completion.

As part of this NUE project, safety assessments are performed. Starting with an initial safety assessment and the successful two-channel NUE demonstration irradiation, it is expected that the existing safety analyses for NU fuel documented in the Qinshan Safety Report are insignificantly affected by using NUE fuel in the full core at Qinshan CANDU reactors. However, to provide confidence and to meet regulatory requirements, four limiting cases for the NUE core are determined and analyzed, confirming that the impact of using NUE fuel in the full core on the current safety analysis results is negligible. Based on the activities completed to date, the full core implementation of NUE fuel is expected to have an insignificant impact on the operation, licensing and overall safety case for Qinshan Units 1 and 2 using NU or NUE, or the transition of NU/NUE fuel and vice versa.

Through this NUE project, Candu has confirmed that NUE fuel can successfully be used in CANDU reactors to provide power from an otherwise 'waste' product with little to no changes in the reactor, as demonstrated in the Qinshan CANDU reactors. That is, the NUE fuel provides an environmental benefit by using Light Water Reactor (LWR) spent fuel to extract additional power from a used resource. Therefore, the resource is more fully exploiting by using it to generate power in the CANDU reactor. In addition, the NUE fuel has the potential to be more economically favorable than NU fuel. This project clearly demonstrates the flexibility of the CANDU reactor design (Figure 6) and the successful cooperation and collaboration between five international companies; CNNC, TQNPC, CNNFC, NPIC and Candu, and pave the path for further CANDU fuel cycle and Advanced Fuel CANDU Reactor programs in China and the world [3][4].

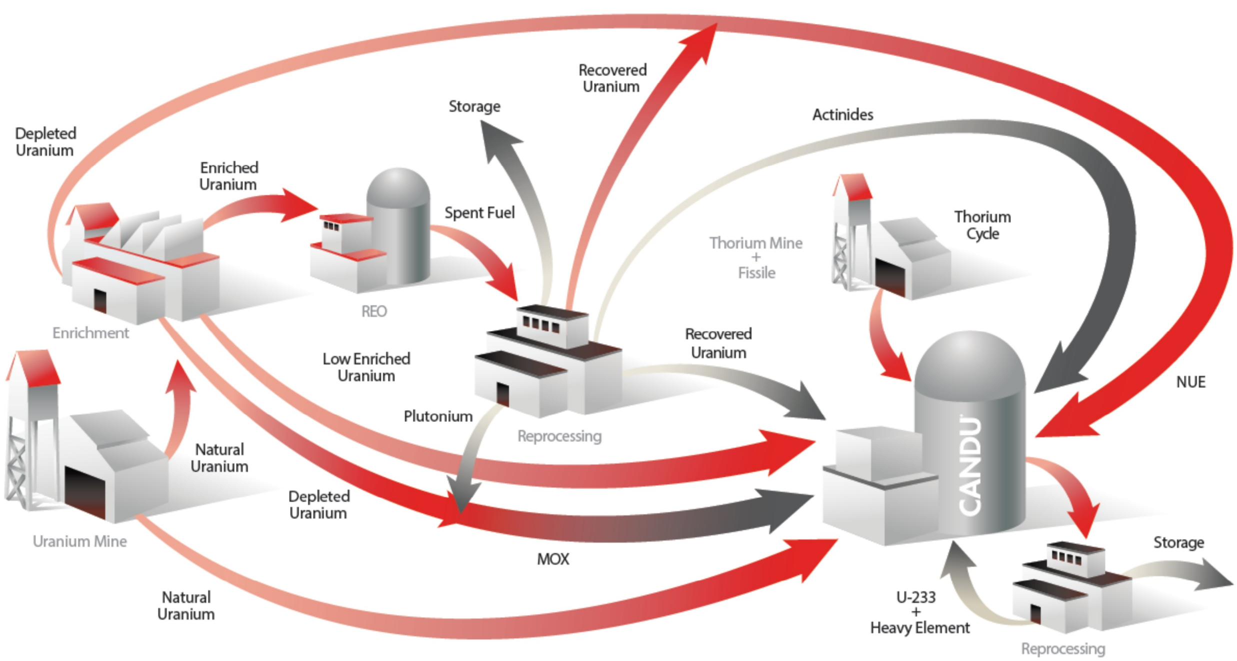

Figure 6 CANDU Fuel Cycle

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