Overview of the Korean Nuclear Fuel Cycle and Recovered Uranium Fuel Program in Korea

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Abstract. Since Kori Unit 1 started to generate electricity on April 29, 1978, the nuclear share of the total electricity generation rate has continued to rise to the current value of 40.3% as of the end of 2006 in Korea. The average availability of the Korean NPPs for the last 8 years ranges around 90% and ranked highly in the world for the past 3 years. However due to the delicate situation that Korean Peninsula faces, the nuclear fuel cycle program has neither been that much ambitious nor successful for the past few decades. As closed fuel cycles using a wet process has not been possible, alternative proliferation-resistant nuclear fuel technology such as DUPIC has been developed and a series of irradiation tests are being carried out at the HANARO reactor. As Korea has not only PWRs as a major vehicle but also CANDUs as minor vehicle, a symbiotic fuel cycle linking PWRs and CANDUs is quite attractive as an supplementary option besides the PWR-SFR linkage concept via a pyroprocess. Another viable symbiotic option is the use of recovered uranium (RU), in CANDUs. Current direct disposal of PWR spent fuel option is expected to result in a steep rise of the spent fuel accumulation reaching 70,000 ton by 2100, but with the fuel recycle based on SFRs, it is expected to reduce to 4,000 ton. In the case of the RU program, the fissile of 0.9 to 1.0% makes it possible for a reuse in CANDU without a re-enrichment. Using RU fuel would produce a significant increase in the fuel discharge burnup of about twice that of NU in a CANDU reactor, thereby increasing the resource utilization and reducing the fuel requirements. Spent fuel volumes and fuelling costs are also reduced by using RU in CANDU reactors. Therefore, the use of RU in CANDU reactors potentially offers economic, environmental and public acceptance benefits for both the front-end and back-end fuel cycles. The major carrier of the RU fuel for CANDU is 43-element CANFLEX, 24 NU bundles of which has already been irradiated in Wolsong for demonstration purpose. The changes in the fuel element and fuel bundle design from 37 to 43 element bundle contribute to the many advantages offered by the 43 CANFLEX bundle.

1. Introduction

In Korea, 16 PWR and 4 CANDU reactors are in operation, 6 PWRs are under construction, and the nuclear share of the total electricity generation amount to 40.3% as the end of 2006[1]. However due to the peculiar situation the Korean peninsula faces, the nuclear fuel cycle program has neither been that much ambitious nor successful for the past a few decades while the amount of spent fuel rises rapidly due to the “wait-and-see” policy for decades. As closed fuel cycles using a wet process have not been possible, alternative proliferation-resistant nuclear fuel technology such as DUPIC[2] has been developed with limited success in an attempt to reduce the LWR and CANDU spent fuel and a series of irradiation tests of sample fuels are being carried out at HANARO reactor at KAERI. As Korea has not only PWRs as the major vehicle but also CANDUs as minor vehicle, a symbiotic fuel cycles linking PWRs and CANDUs are quite attractive as an supplementary option besides the PWR-SFR linkage concept via a pyroprocess. Another viable symbiotic option is the use of recovered uranium (RU), in CANDUs. Current direct disposal of PWR spent fuel option without fuel recycle is expected to result in a steep rise of the spent fuel accumulation reaching 70,000 ton by 2100, but with the fuel recycle based on SFRs, it is expected to reduce to 4,000 ton.
1. Spent Fuel Management Plan and Fuel Cycle

Currently the annual output of the spent fuel in Korea is about 700 tons, more than half of which comes from the 4 units of CANDUs. By the end of 2050 this will rise to 50,000 tons, and it is imperative to develop ways to reduce the amount of spent fuel accumulation. At the end of 2004, the Korean nuclear committee decided to build a medium and low level radioactive waste disposal facility to be completed by 2008, and a spent fuel management policy will be determined in due time considering the direction of the national strategic policy and domestic technology development. Also it was decided that this will be carried out with public consensus through enough discussion, and needs timely action considering that the current storage will be full by 2016. As a result of this, a medium and low level radioactive waste storage facility is being built at the Wolsong site. In parallel to this action, a pyroprocessing program is actively under way with the aim of a construction of an engineering scale of a pyro process by 2016, and a prototype pyro-facility by 2025. Also for the high level waste disposal, a geological disposal system is being conceptually developed using KAERI underground research tunnel as the demonstration of the related technology with the aim of demonstrating an Engineered Barrier System performance by 2016. Along with these programs, a Sodium Fast Reactor (SFR) program is under way within the cooperative frame work of GEN-IV, to complete the conceptual design of KALIMER-600 by 2006, and establish indigenous core, fuel and system concepts by 2009, and a comprehensive and integrated verification of the SFR concept by 2015, aiming at starting the construction of a demonstration SFR by 2028. According to a recent analysis, the amount of spent fuel accumulation with the direct disposal option rises to 70,000 t by the year of 2100 whereas that with SFR employed from 2035 will reduce to 4000 t by the year of 2100.

2. Recycled Uranium Program in Korea

3.1 Background and motivation

Starting with the operation of Wolsong Unit 4 in 1999, now there are 4 CANDU-6 reactors in operation at the Wolsong site in Korea. So about 400 tons of spent fuels are discharged from the Wolsong site, and stored, annually. This large production rate of spent fuel has created a spent fuel storage problem. Therefore it has become necessary to develop a new advanced fuel for a reduction of the current spent fuel volume production rate.

The use of recovered uranium (RU) in CANDU is an excellent example from the environmental 3R’s (recycle, reuse, reduce) point of view. The total amount of RU produced from reprocessing operations in Europe and Japan is expected to be around 25,000 tons by the year 2000 with additional quantities arising from a reprocessing operation in another country [3]. RU fuel offers a very attractive alternative to the use of natural uranium (NU) and slightly enriched Uranium (SEU) in CANDU reactors because the fuel’s economy is expected to improve even more through the use of RU. RU, with about a 0.9 w/o $\text{U}^{235}$ enrichment, results in an average discharge burnup of about twice that of NU in a CANDU reactor, thereby increasing the resource utilization and reducing the fuel requirements. Spent fuel volumes and fuelling costs are reduced by using RU in CANDU reactors. Therefore, the use of RU in CANDU reactors potentially offers economic, environmental and public acceptance benefits for both the front-end and back-end fuel cycles [4]. These benefits fit well with the PWR-CANDU fuel cycle synergy requirement [5]. RU also offers a greater flexibility in reactor and bundle designs and a power uprating capability. RU fuel can be packaged into the CANFLEX fuel bundle, since the full benefits of the use of RU in CANDU reactors are achieved through the provision of enhanced margins in the bundle design.

From the late 1990’s, Korea Atomic Energy Research Institute has been developing the technology for a recovered uranium fuel, which is called CANFLEX-RU (Recovered Uranium Fuel In CANDU). CANFLEX-RU uses a CANFLEX fuel bundle which consists of
43 fuel elements. CANFLEX fuel bundle is characterized by a moderately flat radial-power profile, with the outer and intermediate rings consisting of 21 and 14 elements of 11.5 mm in outer diameter (OD) and the inner ring and center rod consisting of 7 and 1 element(s) of 13.5 mm in OD. The CANFLEX bundle assembly and its critical-heat-flux (CHF) enhancement appendages offer higher operating and safety margins than the currently used 37-element bundle, while maintaining a complete compatibility with the existing CANDU reactors [6].

This paper describes the overall development of the recovered uranium fuel CANFLEX-RU in Korea up to now. It contains the design of a fuel element and bundle, a core analysis of a CANFLEX-RU core, a thermal-hydraulic analysis of a CANFLEX-RU containing channel, and finally a safety analysis of a CANFLEX-RU core [7].

3. Design of a CANFLEX-RU Fuel Element and Bundle

In the physics analysis of a CANDU-6 reactor with CANFLEX-RU fuel bundles, an analysis methodology and computer code system were investigated and established to carry out a time-averaged core calculation and a preliminary refueling analysis of the equilibrium and transition cores.

4.1 Thermal and Mechanical Analysis

The thermal and mechanical characteristics of CANFLEX-RU fuel such as its element pressure and fuel temperature were analyzed to assure its integrity for the CANDU-6 steady-state operations by using a fuel performance code. Power histories used in the analysis were produced from a reactor physics calculation based on a 4-bundle shift refueling scheme as shown in Fig. 1. As can be found in the Table 1 of reference 6, it is found that the temperature and pressure results were satisfied with the design criterion.

4.2 Recovered Uranium Powder Characteristic

Physical and chemical properties such as an isotope content, density, grain size, and dose rate of the recovered uranium (RU) were analyzed and compared to natural uranium (NU). Table 1 shows that the physical and chemical properties of the recovered uranium are similar to those of the natural uranium in spite of the different isotope content and dose rate between the RU and NU powder. This implies that the fabrication property of RU powder is almost similar to that of NU powder, so the fabrication process used in the fabrication of NU powder can be applied to the RU powder without any modification.

4.3 Compatibility of the CANFLEX-RU Fuel Bundle with the Existing CANDU-6 System

CANFLEX-RU fuel bundle design criteria were established with respect to a compatibility with existing CANDU-6 systems such as a primary heat transport system, a fuel channel, and a fuel handling system. Table 2 summarizes the design parameters and their descriptions which should be compatible with the existing systems.

In order to verify the compatibility of the CANFLEX-RU fuel bundle with the PHTS (Primary Heat Transport System), the fretting wear and corrosion of the pressure tube due to a CANFLEX-RU fuel loading were investigated. From the endurance test of the CANFLEX bundle for 3,000 hours, the resultant fretting wear of the pressure tube was proven to be very
small at about 16 µm and a corrosion was not found because of the low temperature of the bearing pad. The wear of the spacer was also evaluated by the endurance test of the CANFLEX bundle for 3,000 hours. By applying the maximum wear rate observed from the wear and endurance tests, the total time needed to be totally worn out for the spacer was calculated to be about 3,000 full power days. However, since this is longer than the irradiation time of the fuel in the channel, it is expected that there will be no problem from the spacer wear viewpoint.

In order to verify the compatibility of the CANFLEX-RU fuel bundle with the fuel channel, the clearance between the CANFLEX-RU fuel bundle string and the shield plugs was assessed. For the CANFLEX bundle, by comparing the maximum length of the fuel bundle string expected with the distance between the shield plugs, so it can be expected that a clearance between the fuel bundle string and the shield plug remains.

In order to verify the compatibility of the CANFLEX-RU fuel bundle with the fuel handling system, the strength of the endplate of the bundle was simulated by using a finite element analysis based on an experimental boundary condition. Figure 2 shows the simulation result of the von-Mises stress contour of the endplate. The maximum stress caused by the hydraulic drag force at the time of a refueling was 329 MPa and this is lower than the ultimate strength of 423 MPa. From this result, the CANFLEX-RU bundle is expected to have an enough strength to maintain its structural integrity.

5. Reactor Physics Design and Analysis

5.1 Investigation of the Reactor Analysis Methodology

In order to develop the reactor analysis methodology and code system, a feasibility study for the lattice and incremental cross sections, a core analysis code, and an analysis of the basic lattice parameter of the reactor physics for the CANFLEX-RU fuel were carried out. The difference between the calculated and measured reactivity of the various types of control devices during the Phase-B post simulation of Wolsong Units 2, 3, and 4 was analyzed by using the physics code systems of WIMS-AECL/DRAGON/RFSP and WIMS-AECL/MULTICELL/RFSP, where the DRAGON code was developed based on a theoretical basis and the MULTICAL code was developed based on an empirical basis for a natural uranium fuel. Figure 3 shows a schematic diagram of the WIMS-AECL/DRAGON/RFSP code system. It was found that the two code systems predicted similar results within a very small difference. It could be concluded that the DRAGON code can be used as a general purpose incremental cross section generation tool not only for a natural uranium fuel but also a recovered uranium fuel.

5.2 Time-Averaged Core Analysis of the CANFLEX-RU Fuel Core

To carry out a time-averaged core analysis of the CANFLEX-RU fuel implemented in a CANDU-6 core, the impact of a uranium isotope variation of the CANFLEX-RU fuel on the CANDU-6 power distributions was evaluated and a preliminary assessment of the reactivity control device and the adjuster system performances of the CANDU-6 CANFLEX-RU core were also investigated. Impacts of the uranium isotope variations of the CANFLEX-RU fuel in CANDU on the average exit burnup and power distributions have been assessed to observe the expected maximum variations (EMV) of the channel and bundle powers. As a result, it is shown that the effects of U-234 and U-236 are so small that they can be disregarded. For the U-235 isotope, it is found that, for a ±0.1w/o variation in U-235 content, the EMVs in the
channel and bundle powers were up to 0.6% and 1.5%, respectively, and for a ±0.2w/o variation in U-235 content, the EMVs were up to 1.3% and 3.2%, respectively.

5.3 Preliminary Refueling Analysis

A feasibility study for a 4 bundle shift refueling scheme was performed for an equilibrium core with CANFLEX-RU fuel and for a transition core which is changed from the existing 37 element NU fuel to CANFLEX-RU fuel. Concerning the operating limits on the MCP, MBP, and CPPF, a 4-bundle shift refueling scheme is feasible to refuel the CANFLEX-RU fuel bundles into an operating CANDU-6 reactor. A schematic diagram of the calculation process for the transition core from the 37 element NU fuel to CANFLEX-RU fuel is shown in Figure 4. It is shown that all the fuel element powers are below the SCC threshold curve for a normal operation and for a power-increase, except that the power boost for some of the ring-4 (outermost ring) elements is above the SCC threshold as shown in Figures 5 and 6. Considering the fact that fuel defects occur when both results for the two envelopes violate the SCC threshold curve simultaneously, no defect of the CANFLEX-RU fuel bundles is expected in the 4-bundle shift refueling scheme. However, by considering the CPPF behavior, a transition core simulation shall be carried out to find a reasonable CPPF behavior for the 4-bundle shift refueling scheme, or to find a reasonable scheme of other refueling shifts.

6. Thermalhydraulic Analysis of the CANFLEX-RU Fuel Channel

Thermalhydraulic (T/H) analysis for the CANFLEX-RU fuel channel includes the set-up of an analysis basis/methodology, the production of basic data, the T/H analysis of a CANDU-6 fuel channel with CANFLEX-RU fuel bundles, and the T/H analysis of a CANDU-6 fuel channel with CANFLEX-RU fuel bundles and 37 element NU bundles.

6.1 Establishment of the T/H Analysis Basis and Methodology

The analysis basis and methodology have been set up and the basic T/H data were produced for the development of the CANFLEX-RU fuel. Design criteria related to the T/H analysis consist of a pressure drop of the fuel bundle, a critical power ratio, a stability of the flow, a fuel channel flow rate, and a fuel temperature. It was found that the existing T/H design criteria for the CANDU-6 reactor with the natural uranium fuel bundles would be satisfied for those with the CANFLEX-RU fuel bundles. In addition, the existing KAERI/AECL T/H experimental data for the CANFLEX-NU fuel and the recent NUCIRC code were found to be applicable for the T/H analysis of the CANFLEX-RU fuel bundle.

6.2 T/H Analysis for the CANFLEX-RU Fuel Implemented Core

The thermal-hydraulic characteristics of the CANDU-6 fuel channel with CANFLEX-RU fuel bundles were analyzed to determine the models for a pressure drop and critical heat flux for the CANFLEX-RU fuel bundle in the NUCIRC code. Through the analysis, the following T/H variables were calculated such as the distributions of the channel flow, quality, critical channel power (CCP), critical power ratio, and the effects of the pressure tube creep and bearing pads height on those distributions.

The CCP of the CANFLEX-RU fuel bundle with low bearing pads in height is expected to be about 2%, 6%, 8% higher than that of the 37-element fuel bundle for various pressure tube creep conditions[8]. The increase is mainly due to the critical heat flux (CHF) enhancement and the axial power distribution of the CANFLEX-RU fuel bundle. The CCP of the CANFLEX-RU fuel bundle with high bearing pads in height was also estimated to be
about 4%, 8%, 14% higher than that of the 37-element fuel bundle in the uncrept, 3.3% crept and 5.1% crept pressure tube, respectively\cite{8}. So, an increase of the bearing pad height would increase the CCP by about an additional 2%.

6.3 T/H Analysis of a Mixed Channel with CANFLEX-RU Fuel and a 37 Element Fuel

The thermal-hydraulic characteristics for the CANDU-6 mixed fuel channel with the CANFLEX-RU fuel and 37 element fuel were analyzed to elucidate the distributions of the channel flow, quality, critical channel power (CCP) and critical power ratio (CPR) based on the calculation results under the transition core power conditions for the mixed fuel channel models. The CCP of the mixed fuel channel is shown to be greater than that of the fuel channel loaded with only 37 element fuel bundles, but the CPR is shown to be a little decreased or increased because of a high channel power in the transition core.

7. Summary and Conclusion

Due to the delicate situation that Korean Peninsula positioned, the nuclear fuel cycle program has neither been that much ambitious nor successful for the past few decades. As closed fuel cycles using a wet process have not been possible, alternative proliferation-resistant nuclear fuel technology such as DUPIC has been developed and a series of irradiation tests are being carried out at the HANARO reactor. As Korea has not only PWRs as the major vehicle but also CANDUs as a minor vehicle, a symbiotic fuel cycle linking PWRs and CANDUs is quite attractive as an supplementary option besides the PWR-SFR linkage concept via a pyroprocess. Another viable symbiotic option is the use of recovered uranium (RU), in CANDUs. Current direct disposal of the PWR spent fuel option is expected to result in a steep rise of the spent fuel accumulation reaching 70,000 ton by 2100, but with the fuel recycle based on SFRs, it is expected to reduce to 4,000 ton.

In the case of the RU program, direct use of RU without an enrichment is considered as an attractive alternative fuel in CANDU reactors. Especially Korea has both PWR and CANDU reactors. It can therefore exploit the natural synergism between these two reactor types to minimize the overall waste production, and maximize the energy derived from a fuel, by ultimately recycling the spent fuel from its PWR reactors in CANDU reactors.

Korea Atomic Energy Research Institute (KAERI) has developed a CANDU advanced fuel, CANFLEX, through an international collaboration with AECL. CANFLEX fuel bundle improves the local heat flux distribution and heat transfer ability. Thus, if RU is packaged into the CANFLEX fuel bundle, the provision for an enhanced margin in the CANFLEX fuel design will accommodate the full benefits of RU and is expected to achieve an enhanced burnup of twice that of the existing CANDU fuel. Because of this, KAERI started to develop CANFLEX-RU fuel with an international collaboration between KAERI, AECL, and BNFL from the late 90’s.

In order to develop the CANFLEX-RU fuel, a preliminary analysis for the design of the fuel element and bundle, and the reactor physics, and the thermal-hydraulic were carried out by KAERI during late 1990s. From the study, it is expected that the CANFLEX-RU fuel can provide lots of benefits, especially in terms of a reduction in a fuel cost and a spent fuel volume and an increase in the fuel cycle synergy effect between PWR and CANDU reactors in Korea.
REFERENCES


Table 1 Physical and Chemical Properties of the RU and NU Powders

<table>
<thead>
<tr>
<th>Properties</th>
<th>RU Powder</th>
<th>NU Powder</th>
<th>RU/NU Ratio</th>
</tr>
</thead>
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<tr>
<td>U⁰²³² (ng/gU)</td>
<td>0.7</td>
<td>N/A</td>
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<tr>
<td>U²³⁴ (g/100gU)</td>
<td>0.0132</td>
<td>Not Detected</td>
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<tr>
<td>U²³⁵ (g/100gU)</td>
<td>0.966</td>
<td>0.725</td>
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<tr>
<td>U²³⁶ (g/100gU)</td>
<td>0.331</td>
<td>N/A</td>
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<tr>
<td>U²³⁸ (g/100gU)</td>
<td>98.688</td>
<td>99.274</td>
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<tr>
<td>U-Factor (g/100gU)</td>
<td>87.23</td>
<td>87.33</td>
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<tr>
<td>Pour Density (g/cm³)</td>
<td>1.18</td>
<td>1.14</td>
<td></td>
</tr>
<tr>
<td>Surface Area (m²/g)</td>
<td>3.53</td>
<td>5.7</td>
<td></td>
</tr>
<tr>
<td>Particle Size (µm)</td>
<td>2.9</td>
<td>2.2</td>
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</tr>
<tr>
<td>O/U Ratio</td>
<td>2.07</td>
<td>2.09</td>
<td></td>
</tr>
<tr>
<td>Green Density (g/cm³)</td>
<td>5.78</td>
<td>5.9</td>
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<tr>
<td>Sintered Density (g/cm³)</td>
<td>10.61</td>
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<td>Grain Size (µm)</td>
<td>7.87</td>
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<td>Surface Dose Rate (µSv/hr)</td>
<td>37.2</td>
<td>13.6</td>
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<td>Dose Rate at 30cm (µSv/hr)</td>
<td>1.74</td>
<td>0.68</td>
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<td>Dose Rate at 100cm (µSv/hr)</td>
<td>0.34</td>
<td>0.27</td>
<td>1.26</td>
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</table>
Table 2 Compatibility Criteria of the CANFLEX-RU Fuel Bundle with the CANDU-6 System

<table>
<thead>
<tr>
<th>System</th>
<th>Design Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compatibility with the primary heat transport system</td>
<td>Pressure drop of fuel bundle string</td>
<td>Should be less than the most frequent pressure drop allowance</td>
</tr>
<tr>
<td></td>
<td>Wear of pressure tube</td>
<td>Not allow the pressure tube wear that failed the integrity of pressure tube</td>
</tr>
<tr>
<td></td>
<td>Wear of spacer</td>
<td>Fuel elements shall remain proper gap between each element</td>
</tr>
<tr>
<td></td>
<td>Corrosion of pressure tube</td>
<td>Pressure tube should remain its integrity</td>
</tr>
<tr>
<td>Compatibility with the fuel channel</td>
<td>Interaction between fuel bundle and pressure tube</td>
<td>Not allow significant fretting or sliding wear of pressure tube, and significant fretting wear of bearing pads</td>
</tr>
<tr>
<td></td>
<td>Pressure tube rolled joint</td>
<td>Fuel bundle shall pass the rolled joint of the pressure tube</td>
</tr>
<tr>
<td></td>
<td>Interaction between fuel string and shield plugs</td>
<td>The length of the fuel bundle string less than the distance between shield plug faces</td>
</tr>
<tr>
<td>Compatibility with the fuel handling system</td>
<td>Fuelling machine sensor, side-stops and pusher</td>
<td>Fuel bundle shall be geometrically compatible with fuelling machine side-stop assembly consisting of a sensor, two side-stops and a pusher</td>
</tr>
<tr>
<td></td>
<td>Fuel bundle string strength against side-stops</td>
<td>Not allow significant deformation of fuel bundles</td>
</tr>
<tr>
<td></td>
<td>Fuel bundle strength under refueling impact</td>
<td>Not allow significant deformation of fuel bundles</td>
</tr>
<tr>
<td></td>
<td>Cross-flow at liner tube</td>
<td>Not allow mechanical failure of the fuel bundle subject to cross-flow inside liner tube</td>
</tr>
<tr>
<td></td>
<td>Increased flow during Refueling</td>
<td>Not allow significant fretting wear of fuel bundle and pressure tube</td>
</tr>
</tbody>
</table>
Figure 1 Element Power-Burnup History of the CANFLEX-RU Fuel

Figure 2 von-Mises Stress Contour of a CANFLEX-RU Bundle, Downstream Endplate
Do you want to include incremental XS for Reactivity Control devices

WIMS-AECL Calculation for XS

XS for Fuel bundle and reflector region

collapsing into 2 group XS by condens and wrfsp subprograms

Collapsed XS for Lattice and Reflector

Input files for Natural U bundle Depleted U bundle

Input file for reflector region incremental XS

Fuel material Burnup Property

DRAGON Calculation for each reactivity control devices

Incremental XS for Devices

RFSP Calculation

Figure 3 WIMS-AECL/DRAGON/RFSP Code System
Figure 4 Flow Chart for the Transition Core Analysis from the 37 Element NU fuel to the CANFLEX-RU Fuel
Figure 5 Element Power Distribution in the Transition Core of the CANFLEX-RU Fuel

Figure 6 Element Power Increase Distribution in the Transition Core of the CANFLEX-RU Fuel