Toward Developing a Next Generation Computer Code for Fuel Analysis

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Abstract

A three-dimensional fuel element performance analysis computer program (code) has been developed at Candu Energy, using the finite element method, especially for application to pellet-cladding interaction and load-following operation. This code is applicable to both PWR and CANDU fuel rods; moreover, the code covers both steady-state and transient conditions. The finite element platform of the computer code has been developed first, and specific performance models are then plugged into the finite element platform. Candu Energy intends to extend this element-based computer code to the bundle-based computer code, by adapting functionality models, which have been developed and used in individual computer codes, to the finite element platform. This paper describes the combination method of individual tools to create the bundle-based analysis code that can be used for fuel analysis under various operation conditions, from normal operation to anticipated operational occurrences and to the postulated events. Some preliminary results are also presented.

1. Introduction

Several computer codes have been developed at Candu Energy for use in fuel safety analysis under various conditions including normal operation, anticipated operational occurrences (AOO) and postulated events. Fuel analysis codes are used to demonstrate that the fuel is being operated within the condition of the operating limits. The accuracy of the analysis depends to a great extent on the qualification of the computer codes used.

CANDU industry has developed a generic process for computer code validation; as a result, qualified computer codes, called Industry Standard Toolset (IST), have been used. The IST codes for fuel analysis include ELESTRES [1] for fuel element analysis for normal operation, ELOCA [2] for fuel element analysis for postulated accidents and SOURCE [3] for steady-state and transient fission gas release analysis.

Non-IST computer codes are also used for specific analysis of fuel behaviour, for example, BOW code [4] is used for analysis of bundle deformation (e.g., element bow, droop), FEAT [5] for assessment of fuel local temperature(e.g., end-temperature peaking analysis), FEAST [6] for assessment of fuel local stress analysis, especially at the sheath ridge or at the endcap-to-sheath weld area.

Most of these fuel analysis codes were developed based on the past legacy code versions whose major framework was developed back in 1980's or 1990's. The recent code development activities include improvement of performance of models or numerical algorithms. Integration of different codes has not been a major focus in the past codes development activities.

There is therefore a need to improve the current fuel analysis codes. The following requirements are identified by various stakeholders:

- The need for a tool for complete simulation of a fuel bundle geometry. Some computer codes are applicable to only restricted geometries (e.g., pellet mid-plane cross section) and some to the full length of a bundle. Assumptions, which are made to cover inconsistent geometric conditions between computer codes, affect the accuracy of code's prediction;

- The need for a comprehensive simulation for a full range of operating conditions, from normal operation to AOO and to postulated events. Available computer codes may not address the full range of conditions that may be encountered for some operational occurrences. A continuous calculation-process from normal operation to abnormal operation (and to postulated high-temperature events) will also minimize possible errors;

- The need for the communication between tools used in different discipline groups, e.g., including feedback from thermalhydraulics and reactor physics analysis. Appropriate communication among fuel codes, thermalhydraulic codes, and reactor physics codes requires the entire configuration of a fuel bundle in three dimensions (radial, azimuthal and axial) to be considered;

- The need for improving accuracies in codes predictions. Some computer codes show relatively large deviations from the results observed from experiments. It is therefore necessary to improve the accuracies of such codes with better defining the code uncertainties in order to quantify margins; and

- The need to extend the range of applicability of a code to demanding conditions that are beyond the expected operating conditions.

This paper describes a proposed next generation fuel code that can address the above items.

2. Proposed Individual Codes Combination Method

In order to satisfy the above needs for fuel analysis codes, we have established general guidelines as follows:

- Maintain the capability of the three-dimensional full-length analysis;

- Include both low temperature/steady-state and high-temperature/transient functionalities in one code; and

- Include improved performance models that are applicable to demanding conditions beyond the current design/safety analysis conditions.

For the implementation, we take the following approaches:

1) Develop a 3-dimensional fuel-element analysis platform using finite-element method;

2) Adapt fuel performance models as plug-in models to the finite-element platform;

3) Expand an element-based fuel code to a bundle-based computer code, by combining with the existing bundle code (BOW).

These general rules and associated implementation approaches are consistent with the current trend for the development of fuel analysis codes in Nuclear Industry.

Figure 1 illustrates the concept for the development of the next-generation fuel code, based on the above implementation approaches. Two big streams that are independently conducted in the development process are (1) to develop a 3-dimensional, fuel element analysis code, and (2) to extend the functionality of the existing bundle code (BOW) to high temperature transients. The functionalities of available codes (e.g., ELESTRES, FEAT, FEAST, INTEGRITY, etc.) are to be captured in the element analysis code. At the final step, the element-based code will be merged to the extended BOW code and generate the next-generation fuel code.

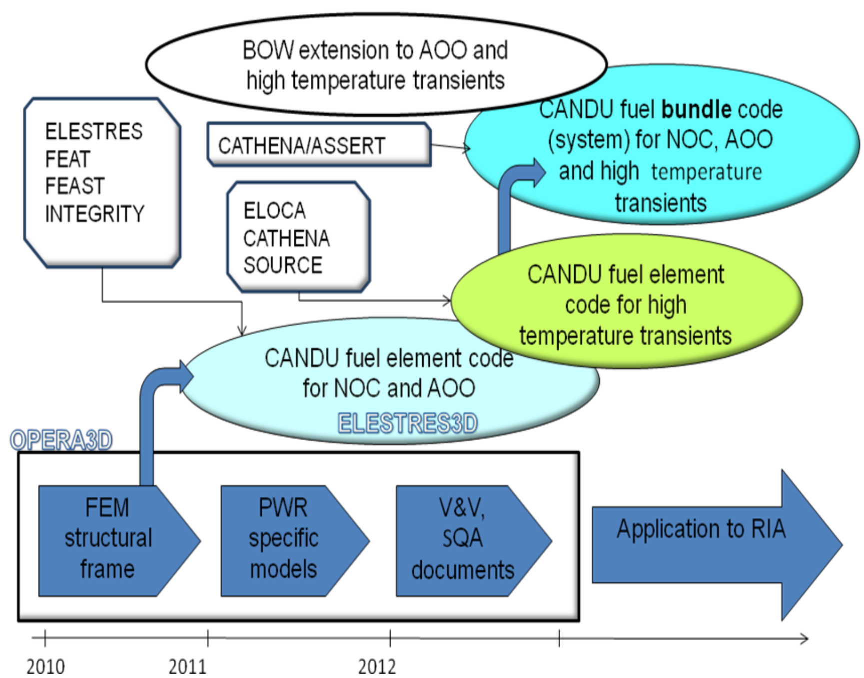


Figure 1 Schematic Concept Diagram for the Development of the Next Generation Fuel Analysis Code

3. Technical Challenges

In developing the 3-dimensional, finite-element platform, special analytical methods are required to solve multiple non-linear problems. In a fuel element, for example, thermal and mechanical phenomena are coupled, and the thermal results are strongly affected by the gap conditions (i.e., open or closed) between the pellet and the sheath. At the same time, the material properties e.g. Young's modules, yield strength, creep rates, etc. are determined as a function of temperature.

To deal with the contact condition, a unique algorithm [7] was developed, which is mathematically proved unconditional convergent for contact phenomena. The governing equation is given in the following linear complementary equation form:

$$\{g\} + [M]\{f_c\} = \{q\} \tag{1}$$

Each element in $\{g\}$ (representing gap) and $\{f_c\}$ (representing normal force) satisfies the following non-negative and complementary conditions:

$$g_i \geq 0,\ f_{ci} \geq 0,\ \ g_i \cdot f_{ci} = 0 \quad (i = 1, \cdots, n_m) \tag{2}$$

A serious of sub-structuring is processed for the implementation of the linear complementary equation. The sub-structuring equations are given in the following form:

$$\begin{bmatrix} K_{oo} & K_{oi} \\ K_{io} & K_{ii} \end{bmatrix} \begin{Bmatrix} u_o \\ u_i \end{Bmatrix} = \begin{Bmatrix} Q_o \\ Q_i \end{Bmatrix} + \begin{Bmatrix} 0 \\ P_i \end{Bmatrix} \tag{3}$$

Equation (3) is based on the assumptions that (i) a set of algebraic equations is obtained from a finite element procedure; and (ii) the displacement vector may be subdivided into two non-empty interior sub-vector u_o and interfacial sub-vector u_i. In Equation (3), Q_o and Q_i are known ordinary load vectors associated with u_o and u_i, respectively; and P_i is unknown constraining force or contact force vector.

Solving the first subset of Equation (3) becomes:

$$\{u_o\} = [K_{oo}]^{-1}(\{Q_o\} - [K_{oi}]\{u_i\}) \tag{4}$$

Substituting Equation (4) into the second subset of Equation (3) becomes:

$$[\overline{K}_{ii}]\{u_i\} = \{\overline{Q}_i\} + \{P_i\} \tag{5}$$

The restructuring process is completed by determining the modified load vector and stiffness vector:

$$[\overline{K}_{ii}] = [K_{ii}] - [K_{io}][K_{oo}]^{-1}[K_{oi}] \tag{6}$$

$$\{\overline{Q}_i\} = \{Q_i\} - [K_{io}][K_{oo}]^{-1}\{Q_o\} \tag{7}$$

Using the sub-structuring method, the number of degrees of freedom in the final linear complementary equations (LCEs) is significantly reduced.

4. Prototyping and Preliminary Results

Efforts for development of individual computer codes are directed to be consistent with the proposed method described in Section 2. Two on-going projects are explained with interim results in this section.

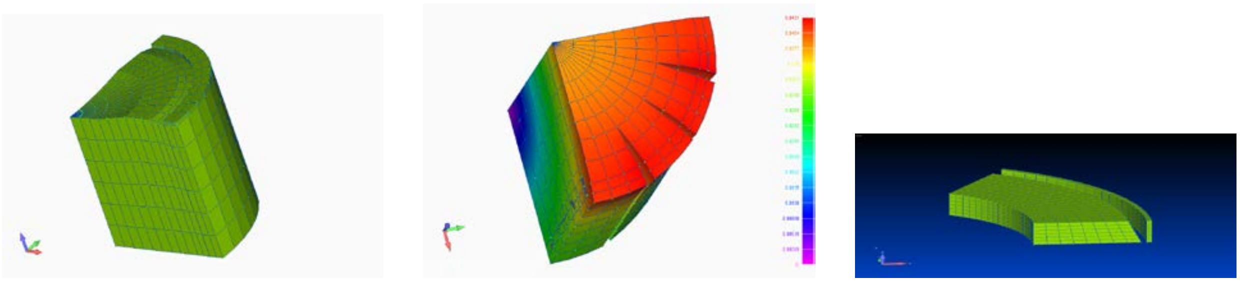
4.1 Development of a 3-Dimensional Finite-Element Platform and the Fuel Element Analysis Computer Codes

The 3-dimensional finite-element platform has been developed for use in the development of a fuel element analysis code. Some key features incorporated in the finite element platform include:

- The three-dimensional finite element method to solve thermal mechanical governing equations;
- Thermal-elastic-creep deformation in the pellet, and also densification and solid fission-product induced swelling;
- Pellet cracking, healing and relocation and its impact on the thermal and mechanical responses;
- Simultaneous solution of the thermal and mechanical governing equations;
- Thermal-elastic-plastic-creep deformation of the sheath, and creep inversion with reduced stress;
- Axial mechanical interaction between pellets;
- Fuel behaviours under both the steady-state and transient conditions; and
- Modelling various pellet shape, e.g., dish, land, chamfer and Missing Pellet Surface (MPS), and also modelling the mixed loading of standard shape (solid cylinder) and special shape (annular, MPS) pellets in a fuel rod.

A PWR fuel element analysis code, named OPERA3D, has been created by plugging in PWR specific performance models to the finite element platform. (This project has been jointly conducted with the KEPCO Nuclear Fuel Company (KNF).) Similar approach is being implemented to create a CANDU fuel element analysis code, named ELESTRES3D, by plugging in CANDU specific performance models to the finite element platform.

Figure 2 illustrates various pellet meshes that are modelled by OPERA3D and ELESTRES3D.



(a) Typical Shape   (b) Pellet Cracking   (3) Missing Pellet Surface

Figure 2 Various Meshes that Are Modelled by OPERA3D and ELESTRES3D

Interim results of OPERA3D

Figure 3 illustrates OPERA3D prediction of pellet deformation and interaction between the pellet and the sheath during a power ramp, in terms of the remaining gap size and the contact force. The test element was a PWR fuel rod base-irradiated to a burnup of about 25000 MWD/MTU at an average rate of around 25 kW/m, followed by power bump to about 80 kW/m in 36 hours. Predicted gap size and contact force at an interface between a pellet and the sheath along the pellet in the middle of the fuel element is examined.

The pellet contacted with the sheath only at the pellet end. The gap size did not monotonically decrease from the pellet midplane to the pellet end along the length of the pellet. This result seems reasonable, based on the fact that the second ridge usually is observed at the midplane of pellets in typical PWR fuel elements.

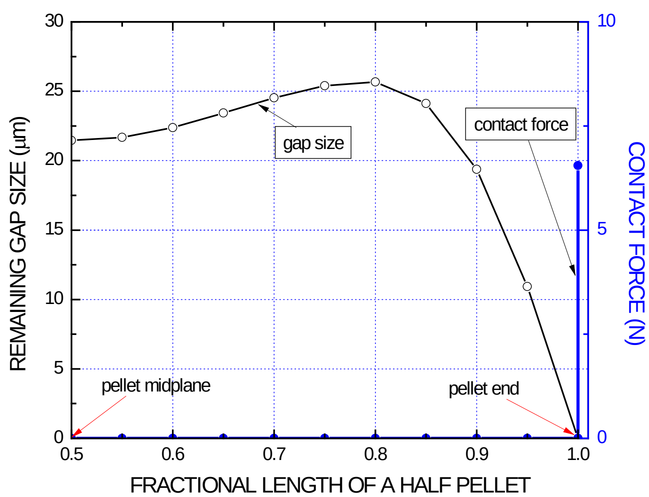


Figure 3 Predicted Gap Size and Associated Contact Force between the Pellet and the Sheath

Interim result of ELESTRES3D

ELESTRES3D has been applied to a simplified test case with which the same results with one-dimensional calculations are expected. Figure 4 shows temperature calculations performed using ELESTRES-IST (left-hand side) and ELESTRES3D (right-hand side). Both results were similar to each other, in terms of trend and magnitude.

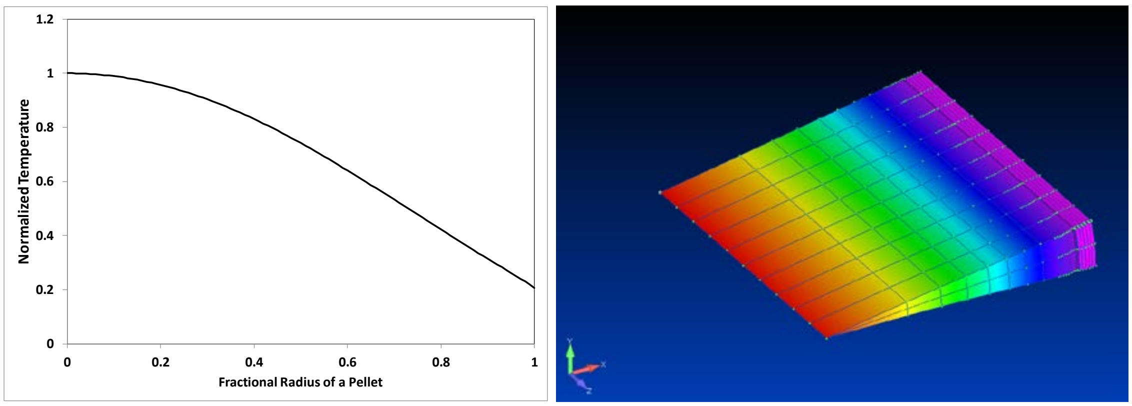


Figure 4 Calculated Pellet Temperature for a Simplified Test Case (peak rating = 58 kW/m), Using ELESTRES-IST (left) and ELESTRES3D (right)

4.2 Extension of BOW for Application to High Temperature Transients

The BOW code [4] predicts bundle deformation in a CANDU fuel string residing in a fuel channel, including fuel element deformation (e.g., element bow, sag, and droop); endplate deformation (e.g., dishing, doming, tilting); contact within a bundle and within a fuel string (e.g., contact forces, locations); bundle droop, and bundle parallelogramming in an aged fuel channel.

The current BOW code accounts for all phenomena occurring during deformation of fuel bundles under in-reactor conditions during normal operation. BOW uses the three-dimensional composite beam model for fuel elements and models 3-dimensional displacements (lateral, axial, and rotational) of fuel elements and endplate rings and webs of fuel bundles (Figure 5).

To extend BOW to high-temperature transient conditions, a number of models need to be developed [8], with focus on:

- Modelling effects of transient conditions on bundle deformation,
- Determining temperature distributions and effective thermal loads,

- Extending contact algorithms to cover sheath-to-sheath contact and sheath-to-PT contact (that may occur at high-temperature conditions);
- Modelling plastic deformation under high temperatures conditions; and
- Accounting for effect of material property change due to high-temperature on bundle deformation.

Transient effects: The transient conditions on CANDU fuel bundles during a postulated event are usually caused by the degraded cooling conditions, which increases bundle temperatures during a very short time period. Such temperature increases will not induce vibration of a fuel bundle. Thus, the effect of the transient condition on fuel bundle deformation is dealt with by considering the temperature gradient change caused by changes in thermal loads on the bundle components (fuel elements and endplates).

Temperature distribution and thermal loads: Under high temperature conditions, a drypatch forms on the sheath surface. The drypatch information, including the temperature in the drypatch, the size and location of the drypatch, is collected from out-reactor tests for post-dryout. With drypatch data collected, the drypatch spreading trends can be assessed, such as the maximum temperature difference between the peak temperature spot and wetted sheath region and the area covered by the drypatch. Additional thermal loads, as a result of the drypatch are calculated from the temperature distribution in the pellet and the sheath.

Extended contact algorithms: Because CANDU fuel bundles are designed to prevent sheath-to-sheath contact during normal operations, the versions of BOW for normal operation models inter-element contacts at bundle mid-plane cross section where there are spacer pads, and also models contacts between outer-ring elements and pressure tube at the cross sections near both ends of the bundle where bearing pads exist. At high temperatures, however, sheath-to-sheath contact and sheath-to-pressure tube contact can occur, due to a number of reasons, for example, (1) reduction in the element flexural rigidity, (2) larger creep at high temperatures, (3) reduction in the yield strength, etc.

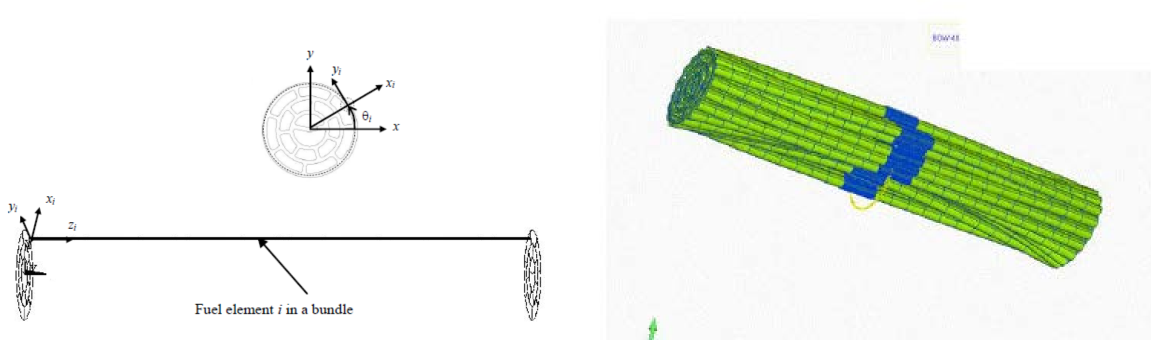


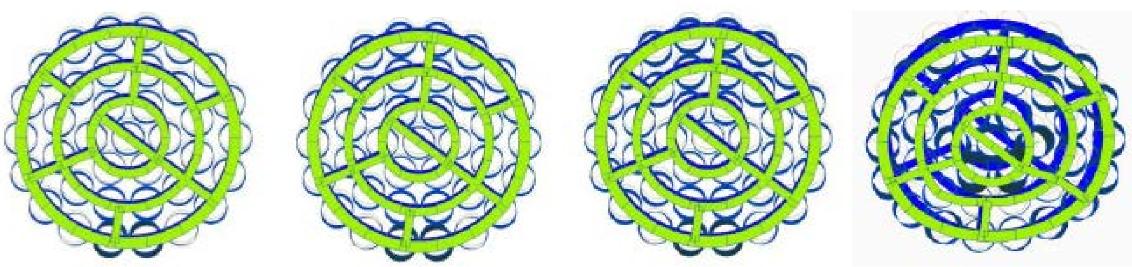
Figure 5 Three-Dimensional Model of the Fuel Element in the Bundle Code BOW

Plastic deformation: Sheath deformation due to plasticity and high temperature creep needs to be included.

Material properties: some properties, e.g., Young's modulus is not sensitive to change in temperature during normal operating condition; however due to a significant change in temperature within a drypatch, all properties needs to be represented as a function of temperature.

The high-temperature transient version of BOW is under development, and updated calculation results using the high temperature version are not available yet.

Figure 6 is the reproduction of the preliminary results [8] using the previous version of the BOW code: front view of the deformed bundle at various temperatures. The undeformed bundle positions are shown in blue for comparison. The deflection increases with temperature, especially at higher temperatures, which is consistent with observations from various out-reactor tests.



(Note: Displacements are 3 times exaggerated)

Figure 6 Front View of Predicted Deformed and Undeformed Bundles at Different Temperatures (350 ^oC, 600 ^oC, 800 ^oC and 1000 ^oC from left to Right)

5. Conclusions

A method for the creation of the next generation fuel codes has been developed at Candu Energy, which includes the following steps:

(1) Develop a three-dimensional analysis, finite-element platform that can be applied to both steady-state and transient conditions;

(2) Develop a fuel element-based code by adapting fuel performance models (that are incorporated existing individual fuel codes) into the finite-element platform;

(3) In parallel with above Step (2), extend BOW functionalities to high-temperature transients; and

(4) Combine the element-based code to BOW and develop a bundle-based fuel code.

One of the key technologies in such development is to manage effectively multiple non-linear solid-to-solid contacts. The method used, called the linear complementary method, can provide unconditionally convergent solutions of multiple non-linear contact problems.

Results from implementation of the proposed next generation fuel code which includes (1) development of a 3-dimensional fuel element analysis code and (2) extension of BOW to high temperature transients are presented in this paper. Interim results shown here are encouraging to further develop this tool.

6. Acknowledgments

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7. References

[1] K-S. Sim, G.G. Chassie, Z. Xu, M. Tayal, C. Westbye, “Progress in Qualifying ELESTRES-IST 1.0 Code: Verification and Interim Results of Validation”, Presented at the 7th International Conference on CANDU Fuel, Canadian Nuclear Society, Kingston, Ontario, Canada, September 2001.

[2] A.F. Williams, “The ELOCA fuel modelling code: past, present and future”, Proceedings of the 9th International Conference on CANDU fuel, Canadian Nuclear Society, Belleville, Canada September 2005.

[3] D.H. Barber, F.C. Iglesias, L.W. Dickson, M.J. Richards and P.J. Reid, “SOURCE IST 2.0 Phenomena Modelling”, Proceedings of the 7th International Conference on CANDU fuel, paper B4007, Canadian Nuclear Society, Kingston, Ontario, Canada, September 2001.

[4] Shouze (George) Xu, Z. Xu, G. Cheng, L. Lai, and S. Yu and D. Wen, “BOW 4.0: Modelling Deformations of Fuel String with Channel Ageing Effects”, Proceedings of the 11th International Conference on CANDU Fuel, Niagara Falls, Ontario, October 2010.

[5] Q. Jiang, L. Lai, Z. Xu and U.K. Paul, “FEAT 4.1: Modelling of Sheath Oxidation and Heat Flow in Candu Fuel Elements”, Proceedings of the 11th International Conference on CANDU Fuel, Niagara Falls, Ontario, October 2010 October.

[6] X. Wang, Z. Xu, Y-S. Kim, L. Lai, G. Cheng, Shouze (George) Xu, “FEAST 3.1: Finite-Element Modelling of Sheath Deformation such as Longitudinal Ridging and Collapse into Axial Gap”, Proceedings of the 11th International Conference on CANDU Fuel, Niagara Falls, Ontario, October 2010.

[7] S. Xu, D.C. Wen, S.D. Yu, "Mixed Complementary Formulation of Lateral Contacts among a System of Parallel Beams", Communications in Nonlinear Science and Numerical Simulation, Volume 13, Issue 10, pp 2308-2319, 2008.

[8] Shouze (George) Xu, Z. Xu, H. Fan, and T. Nitheanandan, "Modelling of Fuel Bundle Deformation at High Temperatures: Requirements, Models and Steps for Consideration", Proceedings of the 11th International Conference on CANDU Fuel, Niagara Falls, Ontario, October 2010.