RECENT DEVELOPMENTS IN ASSERT-PV CODE FOR SUBCHANNEL THERMALHYDRAULICS

Y.F. RAO AND N. HAMMOUDA

Atomic Energy of Canada Limited
Chalk River Laboratories
Chalk River, ON K0J 1J0

This paper summarises recent development of ASSERT-PV, and provides examples of applications to CANDU® fuel bundles in predicting flow, heat transfer and sheath temperatures. The development work is intended to improve computational and phenomenological modelling capabilities of ASSERT-PV in simulating various flow scenarios in CANDU fuel bundles. The latest version of ASSERT-PV can be used for simulations of steady state or transient, subchannel thermalhydraulics in CANDU bundles under conditions up to and including post-dryout heat transfer.

1. INTRODUCTION

Mathematical modelling and numerical simulations of thermalhydraulic phenomena in a nuclear reactor are essential in reactor design and development. System codes are used to describe fluid behaviour in a complete reactor circuit, whereas component codes provide detailed information needed to investigate the local distribution in reactor circuit components.

ASSERT-PV is a subchannel thermalhydraulic computer code capable of predicting the detailed subchannel-level fluid flow and heat transfer in CANDU reactor fuel bundles. It is based on the subchannel concept that has been widely used for fuel-bundle thermalhydraulic analysis, where the fuel bundle is divided into smaller sections called subchannels. The equations of mass, momentum and energy are solved for each subchannel while taking into account the possible inter-subchannel interactions. ASSERT-PV computes the flow and phase distributions in the subchannels of CANDU fuel bundles, and provides a detailed prediction of critical heat flux (CHF), post-dryout (PDO) heat transfer and fuel sheath temperature distributions throughout the fuel bundle.

A major application of ASSERT-PV within AECL is for thermalhydraulic design and licensing of advanced fuels, such as CANFLEX® with slightly enriched uranium (SEU). In particular, ASSERT-PV can be useful to systematically investigate CHF and PDO heat transfer for a range of axial and radial power profiles under conditions of local geometric variations, such as pressure tube creep and fuel element strain. Physical modelling, using conservation equations of mass, momentum and energy, has been very well established. However, the additional constitutive

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relationships required are being continuously developed. The ASSERT-PV development program includes both experimental and analytical projects that are geared towards improving the many constitutive models in the code.

2. BACKGROUND OF ASSERT-PV

ASSERT is a computer code that has been developed to model the subchannel flow and phase distribution in horizontal CANDU channels (Carver et al. 1990). The code has been designed to be general enough to accommodate other geometries and orientations. These include single subchannels of different shapes, and multiple subchannels of CANDU PHWR, PWR and BWR designs, in both vertical and horizontal orientations. As well, the code can accommodate a range of fluids, including single- and two-phase heavy water, light water, various Freons, and two-phase air-water.

ASSERT-PV is based on ASSERT-IV, which in turn originated from the COBRA-IV computer program (Wheeler et al. 1976, Stewart et al. 1977). ASSERT-PV was enhanced to meet the specific requirements for the thermalhydraulic analysis of two-phase flow in the horizontally oriented CANDU fuel bundles. The numerical method in ASSERT-IV can model uni-directional axial flow and bi-directional transverse flow. However, the ASSERT-IV numerical solution is limited to modelling flow structures in which the axial flow is dominant with respect to the lateral flow. This prohibits ASSERT-IV from modelling low axial flow, stagnant flow or axial flow reversals. This limitation has led to the development of a new staggered grid numerical solution scheme based on a pressure-velocity (PV) algorithm. This newer version of ASSERT is designated as ASSERT-PV, and has been used successfully for recirculating flows. ASSERT-PV has been developed to retain the features of ASSERT-IV while employing a more comprehensive numerical solution based on Pressure-Velocity numerical methods (Harlow and Amsden 1971).

The following principal modelling features distinguish ASSERT-PV from COBRA-IV:

1) The lateral momentum equation is written with the gravity term to allow gravity-driven lateral recirculation.
2) The two-phase flow model is based on a five-equation model that can consider thermal non-equilibrium and the relative velocity of the liquid and vapour phases as modelling options. Thermal non-equilibrium is calculated from the two-fluid energy equations for the liquid and vapour. Relative velocity is obtained from semi-empirical models.
3) The relative velocity model is designed to account for the different velocities of the liquid and vapour phases in both the axial and lateral direction. As well, the lateral direction modelling contains features that consider
   a) gravity-driven phase separation or buoyancy drift in horizontal flow,
   b) void-diffusion,
   c) thermal and momentum turbulent mixing, and
   c) void drift (void diffusion to a preferred distribution).

The thermalhydraulic model equations used in ASSERT-PV are derived from the two-fluid formulation presented by Ishii (1977). The ASSERT thermalhydraulic model equations assume that the contributions of turbulent and viscous dissipation, and mechanical work in the energy equations, are negligible. These equations are transformed into a set of finite-difference equations using a subchannel approach similar to that used in COBRA-IV. The cross-sectional area of a fuel-bundle flow channel is divided into a number of parallel interacting subchannels. The subchannels are defined as flow areas between several fuel elements bounded by the element surfaces and imaginary lines joining adjacent element centres. An example of an ASSERT model of subchannels of a 37-element CANDU bundle is given in Figure 1. The subchannel control volumes are established by further subdividing the channel into a finite number of axial increments or nodes. The subchannel control volumes communicate axially with neighbours in the same subchannel and laterally across fictitious boundaries (gaps) with control volumes in neighbouring subchannels.

To numerically solve the ASSERT thermalhydraulic model equations, closure relationships, in the form of additional equations, are required. These closure relationships equalize the number of definitive equations to the number of variables, rendering the model equations solvable. The closure relationships include the equation of state (fluid property) and constitutive relationships, which include correlations for single- and two-phase friction, relative velocity, thermal mixing, wall and interfacial heat transfer, CHF, interfacial area, etc.

The ASSERT-PV solution procedure uses a combination of iteration and direct solution. The channel is repeatedly swept from the inlet to the exit. This outer iteration continues until convergence is achieved or until iteration limit is reached. Successful convergence yields a steady-state solution or one time-step of a transient solution.

3. NEW FEATURES AND SIMULATION EXAMPLES

The latest version of the ASSERT-PV code has the following new or improved features and capabilities:

Enhanced Geometric Capabilities. Enhanced geometric capabilities have been implemented in ASSERT-PV to handle effects on CHF, PDO, pressure drop, flow and phasic distributions, of manufacturing non-conformances as well as design and operational dimensional variations of parameters such as bearing pad and spacer pad heights, fuel element diameters and pressure tube inside diameters. Improvements have also been made to better predict CHF in uncrept and crept channels over a range of radial flux distributions (RFD) and axial flux distributions (AFD). A typical case of axial power distribution and axial variation of a flow channel diameter (due to pressure tube creep) is shown in Figure 2.

New Mixing Models. New mixing models have been implemented in ASSERT-PV to improve the prediction of subchannel phasic mass flux and enthalpy distributions. New models have been introduced for single- and two-phase turbulent mixing, void drift and buoyancy drift (Carlucci et al. 2000). Several modelling options have been provided to permit the user to select the treatment of terms (such as the gravity term in the lateral momentum equation) and user-specified coefficients for models.

Thermal Fuel Model. The original thermal fuel model in ASSERT computes the radial temperature distributions within the fuel sheath, and can be used to include the effects of axial conduction and temperature-dependent fuel conductivity. This model is identical to the one used in COBRA-IV, and does not include any circumferential variation of fuel temperature. Extensive features have been added to include circumferential heat transfer within the fuel element and sheath. The fuel model can accommodate either a real fuel element or an electrically heated element, such as used in laboratory experiments of CHF and PDO studies. It allows flexible computational nodes in the circumferential direction in the fuel and sheath; each fuel element can be assigned a different number of nodes for its circumferential segments. It can also model varying sheath thickness along the axial direction, such as needed in simulating the axial flux distribution in the heated elements used in laboratory experiments.

Post-Dryout Heat Transfer. Post-dryout heat transfer has been improved, and the capability to simulate vapour non-equilibrium has been enhanced for PDO heat transfer calculations. Greater flexibility in simulating developing PDO heat transfer has been achieved though the introduction of an adjustable parameter of an exponential ramp function, used to obtain heat transfer rates in the developing region up to the fully developed PDO. The CHF look-up table and the PDO heat transfer look-up table have been updated using the latest available data.

Transient Capability. Transient capability has been upgraded by introducing an adaptive time step control scheme, in which time step size is determined based on the convergence of the thermalhydraulic solutions or overall energy and mass balances. This scheme allows a larger time step where the time variation of thermalhydraulic parameters is moderate and a smaller time step where the variation is steep, thus enhancing the stability and efficiency of the code in simulating transient events.

With the above new features, ASSERT-PV is now capable of performing the following for both steady-state and transient simulations in crept and uncrept channels:

- critical heat flux (CHF)/critical channel power (CCP) calculations for a fuel channel,
- single-phase and two-phase pressure-drop calculations for typical CCP conditions,
- axial and lateral distributions of void fraction and phasic mass flows,
- PDO heat transfer,
- header-to-header pressure drop boundary condition calculations, and
- analysis of the above with off-nominal radial and axial heat flux distributions.

In addition to the above, ASSERT-PV can be used for the assessment of off-nominal bundle geometry variations on CHF (CCP) and pressure drop due to the following:

- collapsed or worn spacers,
- worn bearing pads,
- element bow and element diametric creep during operation, and
- manufacturing tolerances, including those that result in dimensional non-conformances.

The code is also capable of the thermalhydraulic assessment of new fuel designs (i.e. CANFLEX, low-void fuel, research reactor fuel) to evaluate the effects of:

- number of elements and their layout,
- CHF enhancement (i.e., number and location of enhancement devices), and
- different RFDs (such as for low-void fuel) and AFDs resulting from new fuelling schemes.

Figure 3 presents the axial pressure profiles of a 37-element bundle string at a flow rate of 21 kg/s, and compares the predicted values with measured ones obtained in experiments simulating a full CANDU bundle string. The pressure profile is shown as the local pressure relative to the reference pressure at the channel exit. The agreement between the prediction and measurement is excellent.

Figure 4 shows an example of predicted sheath temperatures compared with measured values in experiments simulating full 37- and 43-element bundle strings, for sheath temperatures at the centre, bottom and top elements. The data adopted for comparison are those from bundles J and K (#10 and #11 from inlet). The mean error and standard deviation between the predicted and measured 48 data points are –4.0 °C and 3.0 °C, respectively.

Figure 5 compares predicted and measured dryout power of a 43-element bundle string, for a range of conditions of inlet mass flux, inlet temperature, and exit pressure. The mean errors and standard deviations between measurement and prediction are also shown in the figure. It should be noted that the large mean errors, or biases, were resulted from employing consistently a single set of model constants or coefficients (for flow distribution, CHF enhancement, etc) to cover all geometries considered in the validation exercise (37- and 43-element bundles, 0%-, 3.3%- and 5.1%-crept channels). For a 43-element bundle, the biases show that the code tends to over-predict dryout power for all the three PT creep conditions. Therefore, in predicting dryout power, the code should be used either as a tool for relative assessment, (e.g., relative percentage reduction of dryout power due to bundle deformation), or should be used with proper compensation included to offset the biases documented in the Validation Report. Investigation of the flow distribution and the CHF enhancement models is currently underway for possible improvement of the models to reduce systematically the biases.

Figure 6 shows an example of fuel element and subchannel locations where dryout occurs for a 37-element bundle string, and compares the predicted locations with those observed experimentally. While the measurements show dryout to occur on elements of the inner and intermediate rings of the 37-element bundle (elements 2, 3, 5, 6, 7, and 19), ASSERT-PV predicts dryout to occur on elements of the inner ring (four elements out of six matched the measurement). The agreement between the predicted and measured locations is reasonable.

Figure 7 shows the effects of modelling radial and circumferential conduction on sheath temperature prediction for a 37-element bundle string under PDO conditions. Results were obtained for the cases of a real fuel element, a simulated fuel element (electrically heated sheath), and a circumferentially constant heat flux assumption. The results show that the circumferential heat transfer within the fuel element and sheath flattens the temperature variation around an element surface, and significantly reduces the PDO sheath temperatures. This illustrates the importance of including the circumferential heat transfer in the fuel and sheath to accurately predict sheath temperatures for fuel bundles under PDO conditions.

Figure 8 shows an example of applications in which the three-dimensional geometric modeling capabilities in ASSERT can be fully utilized. A cross-sectional view of a deformed bundle is shown based on post-irradiation examination (PIE) data of a Bruce-type bundle that resided for two years in one high power position of a reactor core. Along the axial direction of the deformed bundle, the PIE data provide a number of cross-sectional distributions of fuel element bow (element displacement) and element diametric creep for each of the 37 elements at the measured axial locations. Based on the PIE data, a three-dimensional geometric model is generated, and simulation with ASSERT is conducted to assess the effect of the bundle deformation on the onset of dryout power. The assessment results will be discussed in future publications.

4. CONCLUDING REMARKS

The current production version of ASSERT-PV is V3R0 (version 3, release 0), which was released in 2002. ASSERT-PV V3R0 was developed and validated for simulations of steady-state subchannel thermalhydraulics of CANDU bundles under conditions up to and including CHF. Some new features described in this paper, such as PDO, fuel model and transient capability, have been incorporated into a new version V3R1, which will be released in early 2004. ASSERT-PV V3R1 can be used to analyse subchannel thermalhydraulics in CANDU bundles, for steady-state assessment or transient simulations of Loss-of-Flow, Loss-of-Regulation and small LOCA-type scenarios, up to and including post-dryout conditions.

ASSERT-PV can be used to assess:

- thermalhydraulic performance of new fuel designs, and
- effects of geometry variations (e.g., changes in fuel element diameter; changes in inter-element spacer and bearing pad heights; pressure tube creep, etc.).

ASSERT-PV can also be used to provide licensing support for front-line codes in the safety assessment of existing and new fuel designs.

Even though ASSERT-PV has been successfully used to predict pressure drop and dryout power in thermalhydraulic analysis of new fuel designs, its real potential lies in its ability of providing PDO analyses to predict dry patch spreading and fuel sheath temperatures under various scenarios involving conjugate heat conduction in the fuel elements due to partial circumferential dryout. A subchannel code is the only practical tool that can be used to provide accurate information for PDO applications in complex bundle geometries. The one-dimensional approach cannot be relied on for analyses requiring detailed information of bundle dry patch spreading and sheath temperature distributions during PDO, because of the strongly local characteristics of PDO heat transfer.

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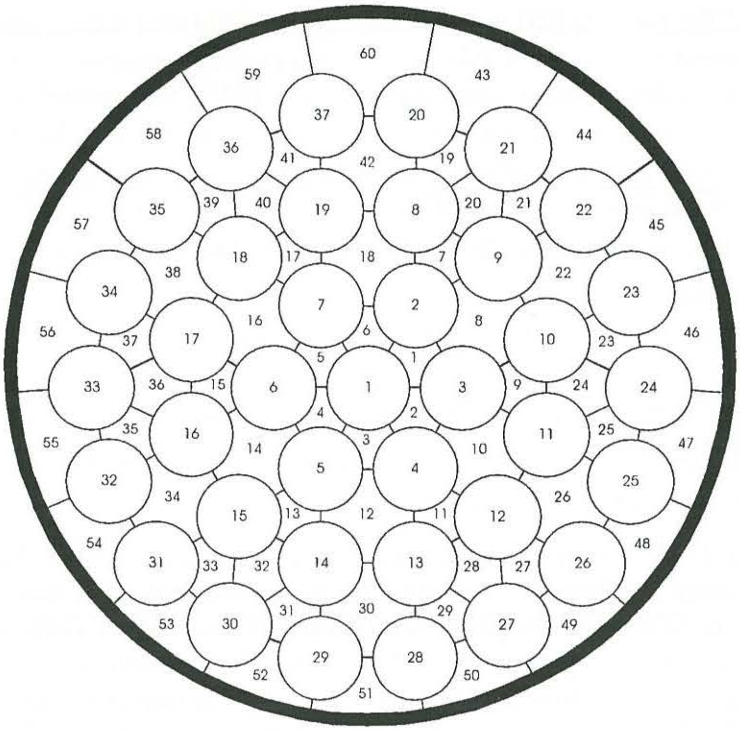

Figure 1. ASSERT-PV Model of a 37-element CANDU Bundle in a Crept Pressure Tube (Maximum Diametric Creep of 5.1%).

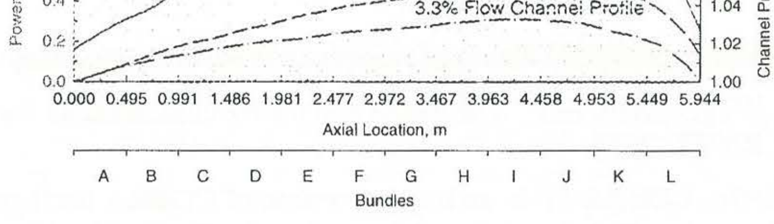

Figure 2. Typical Axial Power Profile and Flow Channel Variations (Maximum Pressure Tube Diametric Creep of 3.3% and 5.1%).

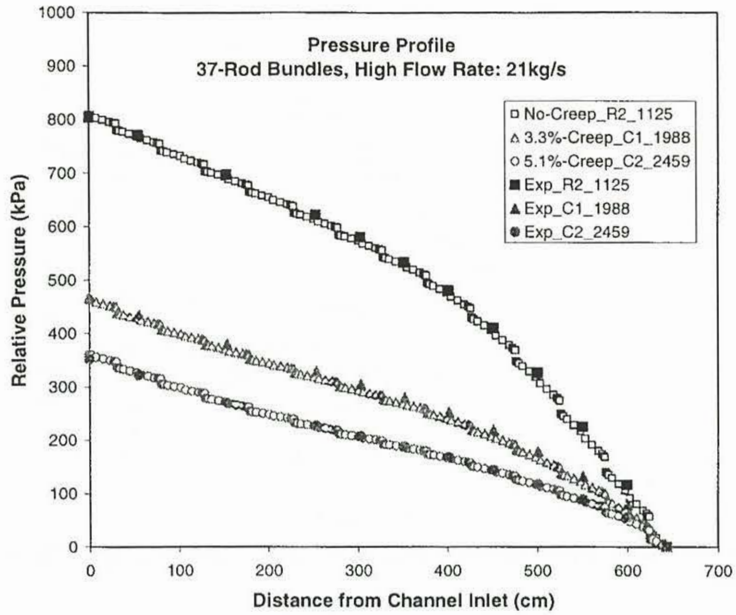

Figure 3. Measured and Predicted Axial Pressure-Drop Profiles Along a 37-Element Bundle String.

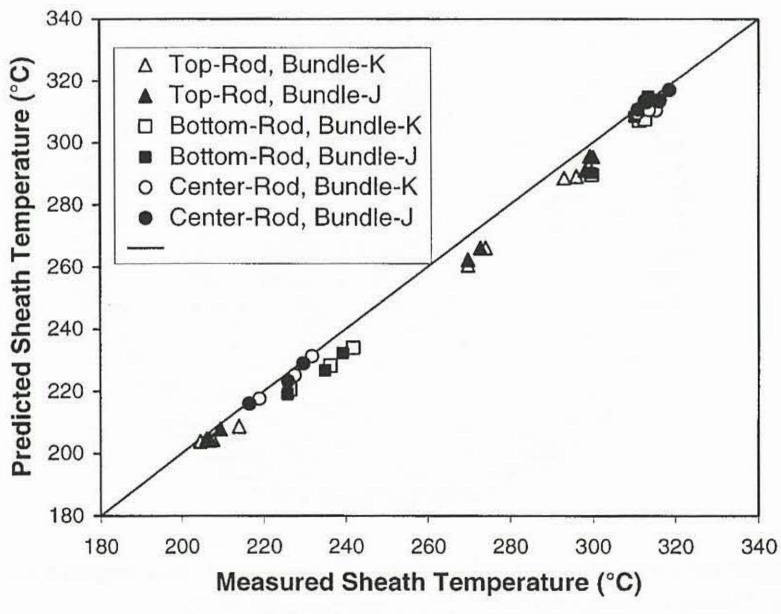

Figure 4. Predicted and Measured Sheath Temperatures at the Centre, Bottom and Top of the Fuel Bundles.

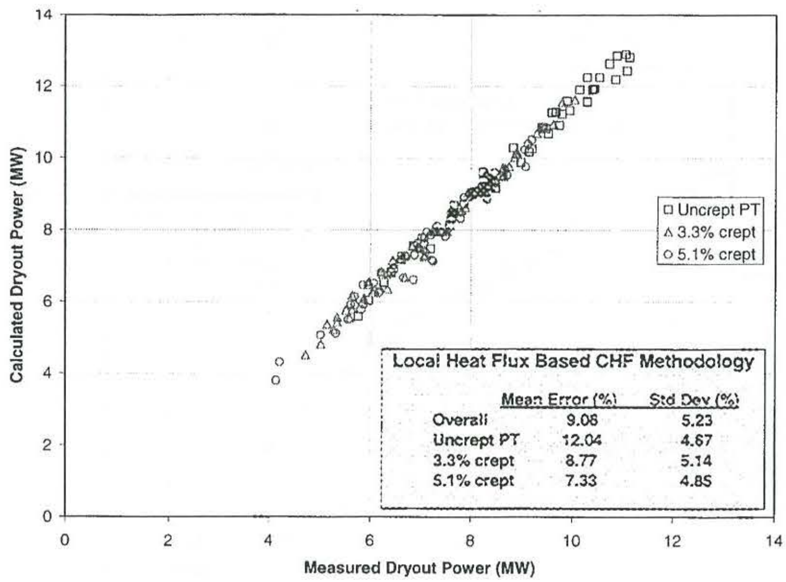

Figure 5. Predicted and Measured Dryout Power in a 43-Element Bundle String.

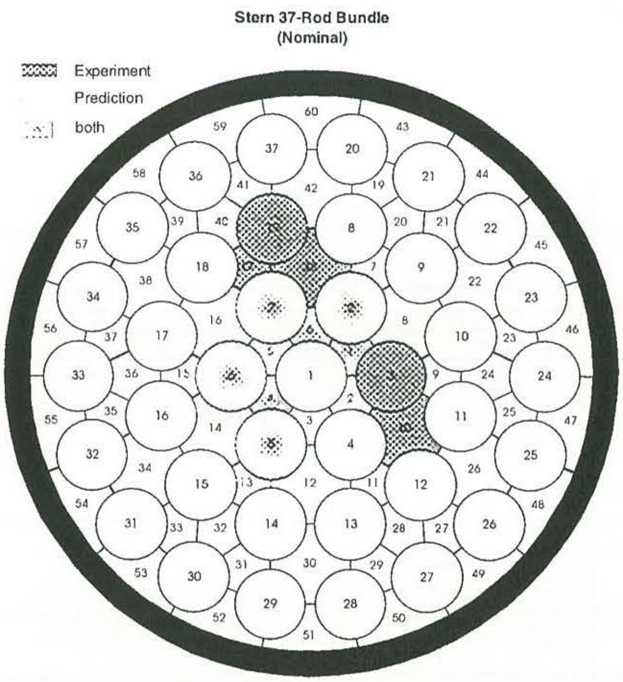

Figure 6. Example of Predicted and Measured Element and Subchannel Locations where Dryout Occur for a 37-Element Bundle String.

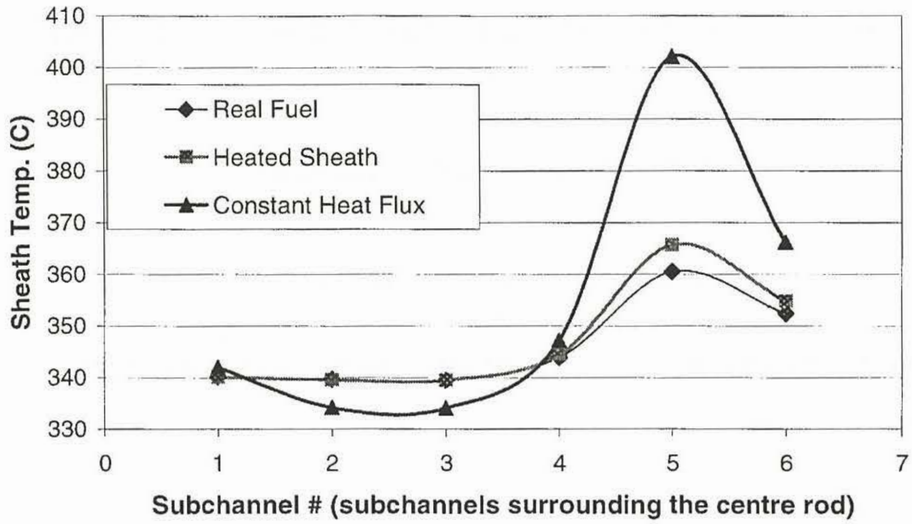

Figure 7. Effect of Fuel Model on Prediction of Sheath Temperatures under PDO Conditions.

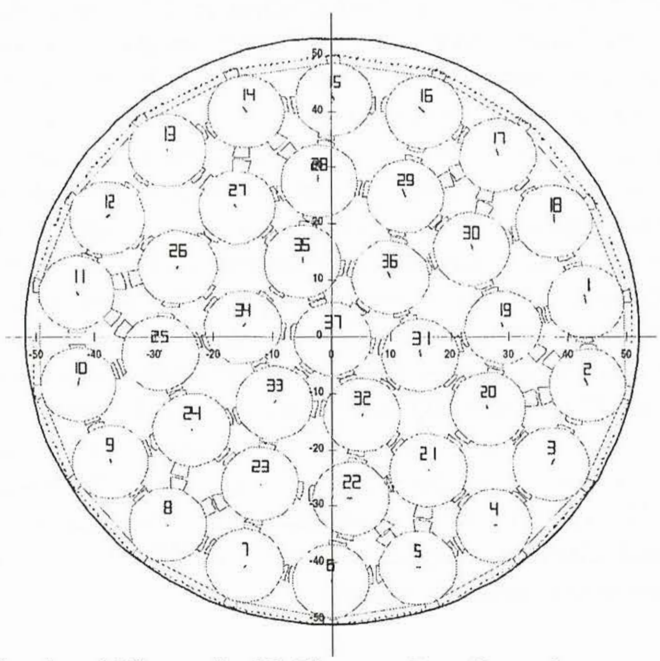

Figure 8. A Cross-Sectional View of a 37-Element Bundle Deformed due to Aging.