Qualification Of FEAST 3.0 And FEAT 4.0 Computer Codes

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ABSTRACT

FEAST (Finite Element Analysis for Stresses) is an AECL computer code used to assess the structural integrity of the CANDU® fuel element. FEAST models the thermo-elastic, thermo-elasto-plastic and creep deformations in CANDU fuel. FEAT (Finite Element Analysis for Temperature) is another AECL computer code and is used to assess the thermal integrity of fuel elements. FEAT models the steady-state and transient heat flows in CANDU fuel, under conditions such as flux depression, end flux peaking, temperature-dependent thermal conductivity, and non-uniform time-dependent boundary conditions.

Both computer programs are used in design and qualification analyses of CANDU fuel. Formal qualifications (including coding verification and validation) of both codes were performed, in accordance with AECL software quality assurance (SQA) manual and procedures that are consistent with CSA N286.7-99. Validation of FEAST 3.0 shows very good agreement with independent analytical solutions or measurements. Validation of FEAT 4.0 also shows very good agreement with independent WIMS–AECL(1) calculations, analytical solutions, ANSYS® (2) calculations and measurement.

1. INTRODUCTION

Both FEAST 3.0 [1] and FEAT 4.0 [2] are AECL computer codes used in design and analysis of CANDU fuel.

FEAST 3.0 is used to assess the structural integrity of the CANDU fuel element. FEAST 3.0 models the thermo-elastic, thermo-elasto-plastic and creep deformations in CANDU fuel. Some examples of FEAST applications include analyses of stress concentrations at the re-entrant corner of sheath-end cap welds, at a sheath

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(1) WIMS-AECL is an AECL reactor physics computer program.
(2) ANSYS is a registered trademark of ANSYS Inc.

circumferential ridge, at junctions between the sheath and the bearing pads, and assessment of residual stresses during long-term storage of fuel bundles.

FEAT 4.0 is used to assess the thermal integrity of fuel elements. FEAT 4.0 models the steady-state and transient heat flows in CANDU fuel, under conditions such as flux depression, end flux peaking, temperature-dependent thermal conductivity, and non-uniform time-dependent boundary conditions. Typical examples of FEAT applications include analyses of temperature peaking in end pellets during refuelling, effect of the brazed void size on sheath temperature, and potential for crevice corrosion [3] between the bearing pad surface and the pressure tube. In addition, FEAT has also been used for thermal calculations of the flux-tilted fuel, and the fuel element heated by an eccentric electric heater.

As both computer programs were needed in the design and qualification analyses of CANDU fuel, formal qualifications including coding verification and validation were performed for both codes, in accordance with AECL software quality assurance (SQA) manual and procedures that are compliant with Canadian Standard Association CSA N286.7-99 [4]. This paper describes the capabilities of the codes and coding verifications, and provides a high level summary of validation methods and results.

2. MODEL CAPABLITIES IN FEAST 3.0 AND FEAT 4.0

2.1 FEAST 3.0 Model Capabilities

FEAST 3.0 calculates the detailed work densities (strain energies), stresses, strains and displacements in two-dimensional (plane or axisymmetric) solids subject to different loads and boundary conditions found in CANDU fuel. The loads include the thermal load (temperature variations) and the mechanical loads. Mechanical loads include distributed load (e.g., pressure), concentrated load (force), specified boundary displacements, and the gravitational load. The boundary conditions include restriction of linear movement in one or more directions, and displacement limits at boundary (set by a gap). Depending on the load conditions, the stress level in the solid modelled by FEAST 3.0 can be either in the elastic or plastic range, with or without creep, i.e., FEAST 3.0 is able to calculate the following stresses, strains and displacements:

- thermo-elastic,
- thermo-elasto-plastic,
- thermo-elasto-creep, and
- thermo-elasto-plastic-creep.

FEAST 3.0 combines several unique features that permit large time steps in even severely non-linear situations involving multiple sources of non-linearity found in nuclear fuel. Such features include (1) a special formulation for permitting many finite elements to simultaneously cross the boundary from elastic to plastic behaviour, (2) accommodation of large drops in yield-strength due to temperature increase, and (3) a three-step predictor-corrector method for plastic analyses. These features reduce computing costs while ensuring a high degree of accuracy.

2.2 FEAT 4.0 Model Capabilities

FEAT 4.0 models steady-state or transient two-dimensional heat flows in a CANDU fuel element. The code is able to simultaneously model: (1) heat flow with radial-distance-dependent heat generation (due to flux depression), (2) heat flow with axial-distance-dependent heat generation (due to end flux peaking), (3) heat flow through multiple bodies (e.g., pellet and sheath), and (4) heat flow in a fuel element with variable material properties (e.g., thermal conductivities of pellet and sheath). Details are discussed below.

<u>Heat Flow with Radial Distance-Dependent Heat Generation (due to Flux Depression):</u> Thermal neutron flux changes across the pellet radius, because of the neutron absorption by uranium, and the plutonium build-up at the pellet surface - a phenomenon called flux depression. As a result of the flux depression, the local heat generation rate varies in the CANDU fuel pellet as a function of the radial distance from the pellet centre. FEAT 4.0 has models (Hammer model [(3)], semi-analytical model, and user input of flux depression data based on physics calculation) to account for the flux depression.

<u>Heat Flow with Axial Distance-Dependent Heat Generation (due to End Flux Peaking):</u> During refuelling and normal operations, thermal neutron flux changes along the axial distance from a bundle end because of the differences in the neutron absorption rate – a phenomenon called end flux peaking. As a result, the local heat generation rate varies in the CANDU fuel pellet as a function of the axial distance from a bundle end. FEAT 4.0 also accepts reactor physics data on end flux peaking and calculates the local heat generation rate based on these data.

<u>Heat Flow through Multiple Bodies:</u> During operation, heat is transferred from the pellet (one solid region), through the pellet-sheath gap, to the sheath (another solid region), that is, heat flow in a fuel element involves multiple bodies. FEAT 4.0 uses gap elements to account for the gap effect on heat flow.

<u>Heat Flow in a Fuel Element with Variable Material Properties:</u> For simulation of steady-state heat flow, thermal conductivity is the only material property required. For simulation of transient heat flow, the required material properties include thermal conductivity, specific heat and density.

[(3)] Hammer model is a flux depression model based on early reactor physics calculation using the HAMMER code.

For a Zircaloy sheath, FEAT 4.0 uses a temperature-dependent thermal conductivity correlation. For UO_2 and (U, Dy)O_2 pellets, FEAT 4.0 uses a thermal conductivity correlation that accounts for the following effects: (1) porosity, (2) temperature, (3) burnup, (4) dissolved fission products (as function of temperature and burnup), (5) precipitated solid fission products (as function of temperature and burnup), and (6) concentration of Dysprosium.

FEAT 4.0 uses a temperature-dependent specific heat correlation for Zircaloy sheath, and a specific heat correlation for UO_2 and (U, Dy)O_2 pellets that is a function of temperature, composition, molten fraction, and oxygen-to-metal ratio. The density of UO_2 or (U, Dy)O_2 pellets is calculated in FEAT 4.0 based on the theoretical density (as a function of Dy concentration) and porosity.

3. VERIFICATION

Verifications of FEAST 3.0 and FEAT 4.0 were performed to ensure that these computer programs function as designed and that their program logic and coding of mathematical expressions are free of errors. To guide the verification exercise, a verification plan for each code was prepared in accordance with the AECL SQA program. Verification plans outline the activities, test cases and schedules to verify the source coding. The verification exercises included the following five methods: line-by-line inspection, static testing, coverage analysis, unit testing and stress testing, as described below.

Line-by-Line Inspection: Line-by-line inspection involves a visual inspection of the code to demonstrate that the software implementation of the conceptual models is free of errors and the coding is consistent with the theoretical description and conceptual model design.

Static Testing: Static testing is the process of analysing a set of source-code files for potential errors (syntax errors, errors in procedures, arguments, data type, common block structure, etc.) without executing the code by use of a set of CASE (Computer Aided Software Engineering) tools such as plusFORT SPAG/GXCHK.

Coverage Analysis: Coverage analysis is the process to assess the percentage of the source code that is exercised by a set of test cases and to uncover any potential remaining errors and inconsistencies in the code. Coverage analysis is performed by use of a CASE tool such as plusFORT SPAG/CVRANAL.

Unit Testing: Unit testing is a process to examine in detail the correctness of the calculation of certain program blocks that are logically related for a well-defined purpose.

Stress Testing: Stress testing is a process to investigate how variations in input parameters translate into variations in output parameters and to uncover potential problems such as discontinuity in an output parameter. Stress testing involves feeding the code with input parameters that change within the application ranges and monitoring how the output parameters behave.

Both FEAST 3.0 and FEAT 4.0 were verified using the above five verification methods. All verification findings were successfully resolved before proceeding to validation.

4. FEAST 3.0 VALIDATION

4.1 Governing Phenomena and Key Output Parameters

Governing Phenomena: A FEAST application requires that several phenomena be considered. Phenomena that are of primary interest are governing phenomena, as given in Table 1.

Table 1 FEAST GOVERNING PHENOMENA AND KEY OUTPUT PARAMETERS

Governing Phenomenon	Key Output Parameter
• Thermo-elastic deformation • Elastic deformation • Elasto-plastic deformation • Stress concentration • Creep deformation • Strain cycle	• Sheath stress • Sheath strain (or displacement)

Key Output Parameters Requiring Validation: Different key output parameters need to be considered for different applications. Key output parameters for all applications were identified in Table 1.

4.2 FEAST 3.0 Models to be Validated and Validation Datasets

Key output parameters given in Table 1 are calculated in FEAST 3.0 by a number of models. Ten models were identified for validation (see Table 2). Data sets were used to validate a code model (or a program component). For example, data set V1-1 was used to validate the model for elastic deformation in a plane solid. All FEAST 3.0 models were validated by 21 validation data sets, as shown in Table 2.

Table 2 FEAST 3.0 CODE MODELS TO BE VALIDATED AND VALIDATION DATA SETS

FEAST 3.0 Code Model	Data Set
Thermal elastic deformation in an axisymmetric solid	V2-2, V2-3, V2-4

FEAST 3.0 Code Model	Data Set
Elastic deformation in an axisymmetric solid under distributed loads	V2-1, V2-5
Elasto-plastic deformation in an axisymmetric solid	V4-1
Thermo-elasto-plastic deformation in a solid whose yield strength drops with temperature increase	V3-4
Elastic deformation in a plane solid (in x-y or r-θ coordinate system)	V1-1, V1-2, V1-3, V1-4, V1-5, V1-7, V1-8
Creep deformation in an axisymmetric solid	V4-2, V4-3, V4-4
Deformation in a solid corresponding to a cyclic load	V1-5
Deformation in the plastic range involving loading and unloading	V3-3
Thermal deformation in a plane solid (in x-y or r-θ coordinate system)	V1-6
Elasto-plastic deformation in a plane solid (in x-y or r-θ coordinate system)	V3-1, V3-2, V3-3, V3-4

The twenty-one validation data sets are divided into 4 groups: (1) Group 1, thermal and elastic deformation in the Cartesian (x-y) or the polar (r-θ) coordinate system, (2) Group 2, thermal and elastic deformation in the cylindrical (r-z) coordinate system, (3) Group 3, elasto-plastic deformation in the Cartesian (x-y) or the polar (r-θ) coordinate system, and (4) Group 4, elasto-plastic and creep deformation in the cylindrical (r-z) coordinate system. These data sets are from analytical solutions and experimental measurements, as seen in Table 3. Many data sets are from the validation of an early version of the FEAST code [5].

Table 3 DESCRIPTIONS OF FEAST VALIDATION DATA SETS

Data Set	Data Set Description	Type of Result
V1-1	Elastic stress and displacement in a short, rectangular cross section cantilever beam under a uniform load P applied at the free end	Analytical
V1-2	Elastic stress and displacement in a beam of rectangular cross-section, simply supported at ends, bent by a distributed load of intensity q	Analytical
V1-3	A concentrated force P acting on the boundary of a semi-infinite slab with a thickness of unity and the force uniformly distributes along the thickness of the slab.	Analytical
V1-4	Stress-concentration near a hole in a large plate under uniaxial tension.	Analytical
V1-5	Elastic strain in a slab corresponding to a load cycle. The slab has length 2L and width W and is under cyclic uniaxial tension load.	Analytical
V1-6	Stress in a slab of length 2L and width 2W with symmetrical linear temperature gradient: $T = q \pm sr$ along the transverse direction	Analytical
V1-7	Similar to V2-1, but in Polar coordinate.	Analytical
V1-8	Two-dimensional photoelastic stress analysis of end caps	Experimental
V2-1	Elastic stress in a long, thick pressurized cylinder with free ends	Analytical
V2-2	Thermal stresses in a long solid cylinder with linear temperature gradient: $T = q + sr$	Analytical
V2-3	Thermal stresses in a solid cylinder with parabolic temperature gradient: $T = q+sr^2$	Analytical
V2-4	Thermal stresses in a long hollow cylinder. linear temperature distribution along radial direction $T=q+sr$	Analytical

Data Set	Data Set Description	Type of Result
V2-5	Strain gauge measured strain profiles near the sheath-end cap weld	Experimental
V3-1	Maximum stress (elastic-plastic) in a large slab with a small circular hole in the centre, subject to uniaxial tension.	Analytical
V3-2	A slab (length 2L, width 2W) under uniaxial tension. Find stress or strain in the slab when failure occurs. Find the elastic-plastic stress with the load.	Analytical
V3-3	Elastic-plastic stress in a slab (length L, width W) under uniaxial loading-unloading	Analytical
V3-4	Stress in a slab of length L and width W under uniaxial loading-unloading. Temperature suddenly increased when load is above the yield strength. The yield strength drops as temperature rises.	Analytical
V4-1	Elastic-plastic stresses in a long, thick, pressurized hollow cylinder	Analytical
V4-2	Axial creep stress during stress relaxation in a cylinder under axial tension, with initial loading stress σ_0.	Analytical
V4-3	Similar to V4-2, but use different m, n	Analytical
V4-4	Stationary creep (m=1, n = 1) stress in a thick closed pressurized cylinder.	Analytical

4.3 FEAST 3.0 Validation Results

FEAST 3.0 calculations were compared with independent analytical solutions or measurements for 21 datasets. They are shown in Figures 1 and 2.

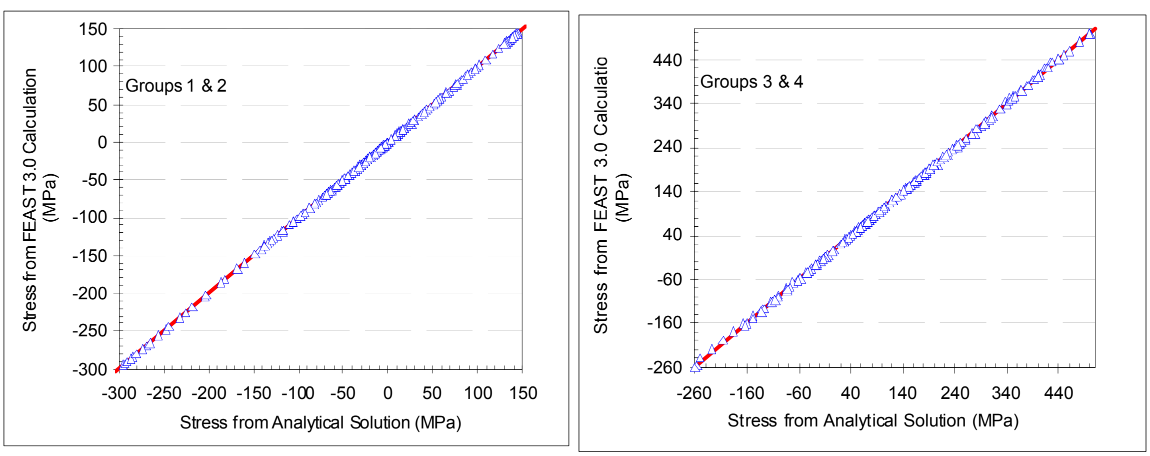

Figure 1 FEAST 3.0 CALCULATIONS AND ANALYTICAL SOLUTIONS

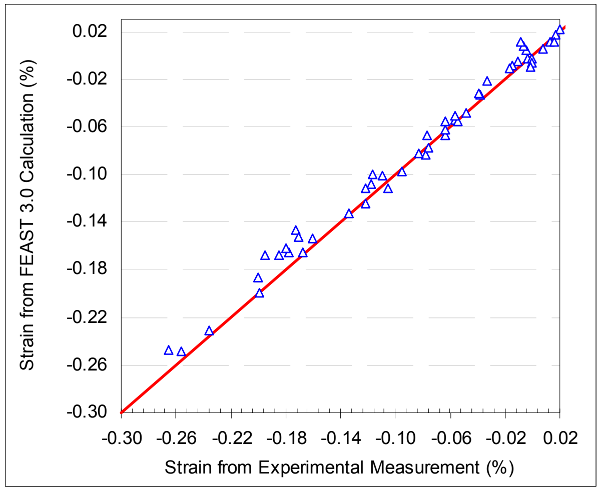

Figure 2 FEAST 3.0 CALCULATIONS AND MEASUREMENTS

In summary, validation results are as follows:

For thermo-elastic analyses (Groups 1 and 2), results of the FEAST 3.0 calculations are in excellent agreement with those of the independent solutions (analytical). The results of the FEAST 3.0 calculation also agree well with the strain-gauge measurements. The uncertainty analysis of results for Groups 1 and 2 shows that

- For a stress range of –295 to 145 MPa with an absolute-stress average of 63.3 MPa, there is only a slight over-prediction by FEAST 3.0 (by 0.044 MPa, a mean error) with a standard deviation of 0.299MPa.
- For a strain range of –0.265% to 0.113% with an absolute-strain average of 0.077%, there is only a slight over-prediction by FEAST 3.0 (by 0.0046%, a mean error) with a standard deviation of 0.008%.

For thermo-elasto-plastic and creep analyses (Groups 3 and 4), results of the FEAST 3.0 calculations are in good agreement with the analytical solutions. The uncertainty analysis of results for Groups 3 and 4 shows that

- For a stress range of –297 to 500 MPa with an absolute-stress average of 184 MPa, there is only a very small over-prediction by FEAST 3.0 (by 0.24 MPa, a mean error) with a standard deviation of 2.19 MPa.

5. FEAT 4.0 VALIDATION

5.1 Governing Phenomena and Key Output Parameters

Governing Phenomena: A FEAT application requires that several phenomena be considered. Phenomena that are of primary interest are governing phenomena, as given in Table 4.

Table 4 FEAT GOVERNING PHENOMENA AND KEY OUTPUT PARAMETERS

Governing Phenomenon	Key Output Parameter
• Diffusion of heat in the pellet and the sheath • Fuel pellet-to-sheath heat transfer • Fission (internal heat generation) • Fuel pellet-to-endcap heat transfer	• Relative heat generation rate across the pellet radius • Pellet temperatures • Sheath temperatures

Key Output Parameters Requiring Validation: Different key output parameters need to be considered for different applications. Key output parameters for all applications were identified in Table 4.

5.2 FEAT 4.0 Models to be Validated and Validation Datasets

Key output parameters given in Table 4 are calculated in FEAT 4.0 by a number of models. Twenty-two models or model combinations were identified for validation (see Table 5). Data sets were used to validate each code model (or a program component). For example, data set V1-1 was used to validate the model for heat flow in a two-dimensional axisymmetric solid. All code models are validated by the 26 validation data sets, as shown in Table 5.

Table 5 FEAT 4.0 CODE MODELS TO BE VALIDATED AND VALIDATION DATA SETS

FEAT 4.0 Code Model	Data Set
Steady-state 2-D heat flow in an axisymmetric solid	V1-1
Steady-state heat flow in an axisymmetric solid with internal heat generation	V1-6, V1-2, V1-3
Flux depression model	V1-4
Steady-state heat flow in multiple axisymmetric bodies separated by gaps	V1-2
Steady-state heat flow in an axisymmetric solid with variable thermal conductivity (temperature-dependent)	V1-3
Steady-state heat flow in an axisymmetric solid with convective boundary conditions	V1-5, V1-2
Steady-state heat flow in a two-dimensional Cartesian or polar coordinate system	V2-1, V2-4, V2-5
Steady-state heat flow in multiple plane bodies separated by gaps	V2-2, V2-4

FEAT 4.0 Code Model	Data Set
Steady-state heat flow in a plane solid with variable thermal conductivity (temperature dependent)	V2-3, V2-4
Steady-state heat flow in a plane solid with specified heat flux at boundaries	V2-4
Steady-state heat flow in a plane solid with adiabatic and convective boundary conditions	V2-2, V2-3, V2-4
Steady-state heat flow in a plane solid with internal heat generation	V2-2
Transient heat flow in r-z coordinate system	V3-1, V4-9
Transient heat flow in an axisymmetric solid due to the variation of the local heat generation rate with time	V3-2, V3-3
Transient heat flow in multiple axisymmetric bodies separated by gaps	V3-4
Transient heat flow in an axisymmetric solid with variable thermal conductivity (temperature-dependent)	V3-5
Transient heat flow in an axisymmetric solid due to time-dependent convective boundary conditions	V3-6
Transient heat flow in a two-dimensional x-y or r-θ coordinate system	V4-1, V4-8, V4-2, V4-3
Transient heat flow in multiple bodies separated by gaps	V4-4
Transient heat flow in a solid with variable thermal conductivity (temperature-dependent)	V4-5
Transient heat flow in a solid due to time-dependent non-uniform temperatures at boundaries	V4-6
Transient heat flow in a solid due to time-dependent heat fluxes at boundaries	V4-7

The validation data sets are from independent results including analytical solutions, WIMS-AECL calculation, ANSYS calculations and measurement. They are divided into four groups: (1) Group 1, steady-state heat flow in axisymmetric solids, (2) Group 2, steady-state heat flow in plane solids, (3) Group 3, transient heat flow in axisymmetric solids, and (4) Group 4, transient heat flow in plane solids. These data sets are from analytical solutions, ANSYS calculations and measurements, as seen in Table 6. Most data sets are from the validation of an early version of the FEAT code [6].

Table 6 DESCRIPTIONS OF FEAT VALIDATION DATA SETS

Data Set	Data Set Description	Type of Result
V1-1	Temperatures in a finite solid cylinder with constant k, surface heated to T_s, two ends at 0°C.	Analytical.
V1-2	Temperatures in inner and outer cylinders, heat generation q" in inner cylinder, outer cylinder cooled by fluid.	Analytical
V1-3	Temperatures in long solid cylinder, $k = k_0[1+ \gamma (T-T_0)]$, heat generation q", surface kept at T_s.	Analytical
V1-4	Local power density as a function of the pellet radial distance in different pellets as functions of burnup.	WIMS-AECL
V1-5	Temperatures in a long hollow cylinder, constant k , inner surface heated by q_1, outer surface cooled by fluid.	Analytical
V1-6	Temperatures in a long solid cylinder, with heat generation q", zero surface temperature T_s.	Analytical
V2-1	Temperatures in a finite slab, constant k, boundary at y = H heated to T	Analytical

Data Set	Data Set Description	Type of Result
	$= T_m\sin(\pi x/L)$, other 3 boundaries at 0 °C.	
V2-2	Temperatures in slabs (inner slab sandwiched by outer slabs), heat generation q" in inner slab, outer slab cooled by fluid.	Analytical
V2-3	Temperatures in infinite slab, k ($k = k_0[1+ \gamma(T-T_0)]$), surface at x = 0 heated to T_1, surface at x = L kept at T_2.	Analytical
V2-4	Temperatures in an electrically heated bearing pad and pressure tube specimen assembly tested in the WECAN Corrosion Research Loop.	Experimental.
V2-5	Temperatures in a long solid semi-cylinder, diameter heated to T_0, surface kept at a lower temperature T_1.	Analytical
V3-1	Temperatures in a finite hollow cylinder, uniform initial T_i, inner surface suddenly heated by q_1, other surfaces cooled by fluid.	ANSYS
V3-2	Temperatures in a long circular cylinder, initially at T_i. $q'' = q''(t)$ suddenly generated, surface cooled by fluid.	ANSYS
V3-3	Temperatures in a cylinder, zero initial temperatures, heat generation rate $q''= q''(t) =A\ e^{-bt}$ for $t > 0$ (b is a constant), surface at zero temperature.	Analytical
V3-4	Temperatures in two concentric long cylinders (e.g., pellet and sheath), separated by a thin gap (gap conductance h_1), q" suddenly generated in inner cylinder, outer cylinder cooled by fluid (T_f, h_2).	Analytical
V3-5	Temperatures at r/R = 0.4 in an initially heated long cylinder with variable k, suddenly immersed in coolant.	ANSYS
V3-6	Temperatures with time in a cylinder, constant k , ρ, and C_p , heat generation q”, surface cooled by fluid (time-dependent h and T_f).	ANSYS
V3-7	Temperatures in a long cylinder, zero initial temperature, surface temperature $T_s=bt$ (b is a constant).	Analytical
V4-1	Temperatures in a finite slab, initially at 0°C, boundary at y = H suddenly heated to $T = T_m\sin(\pi x/L)$, other 3 boundaries kept at 0°C.	ANSYS
V4-2	Temperatures in a semi-infinite slab, initially at 0 °C, $q'' = q''(t)$ suddenly generated, surface at x = 0 kept at 0 °C.	ANSYS
V4-3	Temperatures in an infinite slab (thickness 2L), initially at 0°C, heat generation q'', both surfaces kept at 0 °C.	Analytical
V4-4	Temperatures in inner & outer slabs sandwiching the inner slab, initially at T_i, q'' suddenly generated in inner slab, outer slab cooled by fluid.	ANSYS
V4-5	Temperatures in a semi-infinite solid, k ($k = k_i\cdot[1+\beta\cdot(T-T_i)]$), uniform initial T_i, surface at x = 0 suddenly heated by q_w.	Analytical
V4-6	Temperatures in a slab of thickness 2L, zero initial temperature, both surfaces kept at temperature $T_w=f(t)=bt$ for $t > 0$.	Analytical
V4-7	Temperatures in a finite slab, boundary at x = 0 heated by a heat flux $q = bt$ (b is a constant), other 3 boundaries are at temperature T_w.	ANSYS
V4-8	Temperatures in a long semi-cylinder, initially at T_0, temperature at surface (r = R) suddenly dropped to T_1, diameter kept at T_0.	ANSYS

5.3 FEAT 4.0 Validation Results

FEAT 4.0 calculations were compared with independent analytical solutions and measurements for 26 datasets. They are shown in Figures 3 and 4.

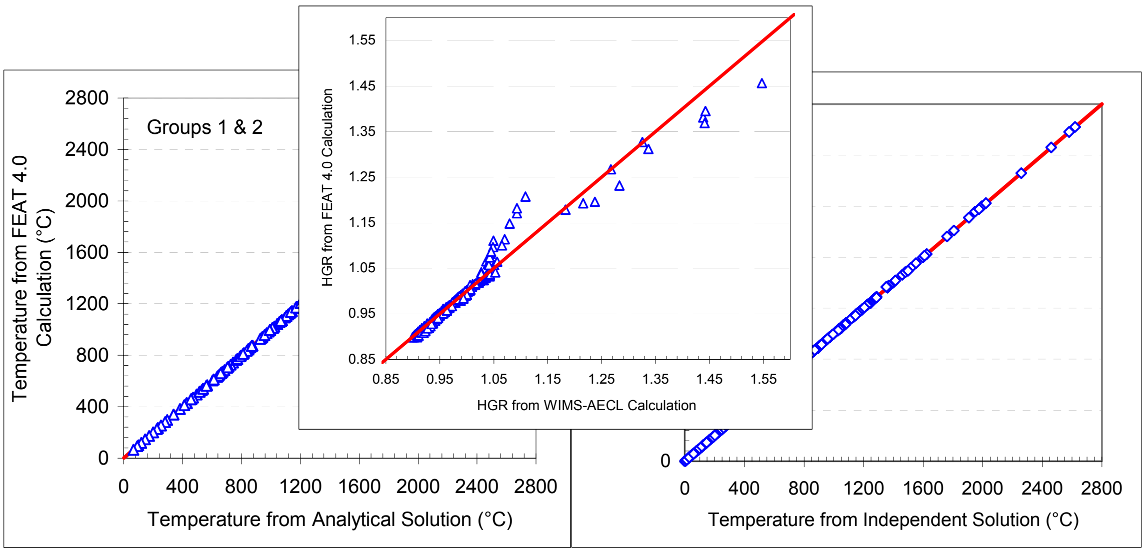

Figure 3 FEAT 4.0 CALCULATED HGR AND WIMS-AECL RESULTS

Figure 4 FEAT 4.0 CALCULATIONS AND INDEPENDENT SOLUTIONS

In summary, validation results are as follows:

For heat flow in the presence of the flux depression, the FEAT 4.0 calculated relative local heat generation rate (HGR), using the Hammer model, match well with those of the WIMS-AECL calculation. The differences between FEAT 4.0 and WIMS-AECL calculations are within the range of –5.9% and 8.9%. The uncertainty analysis of the results shows that

- For HGRs in the range of 0.8996 to 1.547, with an average HGR of 0.996, there is only a small over-prediction by FEAT 4.0, with a mean error of 0.00024 and a standard deviation of 0.020.

For steady-state heat flow (Groups 1 and 2), the FEAT 4.0 calculated temperatures are in excellent agreement with those of the independent solutions, including analytical solutions and one experimental measurement. The uncertainty analysis of results for Groups 1 and 2 shows that

- For temperatures in the range of 65 to 2640°C, with an average temperature of 1358°C, there is only a slight over-prediction by FEAT 4.0, with a mean error of 0.22°C and a standard deviation of 0.87°C.

For transient heat flow (Groups 3 and 4), the results of the FEAT 4.0 calculations are in very good agreement with the independent solutions including analytical solutions and ANSYS calculations. The uncertainty analysis of results for Groups 3 and 4 shows that

- For temperatures in the range of 0 to 2620°C, with an average temperature of 540°C, there is only a very small over-prediction by FEAT 4.0, with a mean error of 0.51°C and a standard deviation of 2.23°C.

6. CONCLUSIONS

Qualification (including verification and validation) of FEAST 3.0 and FEAT 4.0 was performed for the intended code applications, in accordance with the AECL SQA program and CSA-N286.7-99.

FEAST 3.0 was validated using four groups of validation data sets, for two key output parameters: sheath stress and strain. The four groups of validation data sets included thermo-elastic deformation in plane solids and axisymmetric solids, thermo-elasto-plastic deformation in plane solids, and thermo-elasto-plastic and creep in axisymmetric solids. Validation of FEAST 3.0 shows very good agreement with independent analytical solutions and measurements.

FEAT 4.0 was validated for three output parameters including pellet temperature, sheath temperature and relative heat generation rate (HGR) across the pellet radius. Four groups of validation data sets were used. These data sets included steady-state and transient heat flow in axisymmetric and plane solids. Validation of FEAT 4.0 shows very good agreement with independent solutions and a measurement.

Within the prescribed domain of applicability, FEAST 3.0 is suitable for use in modelling the thermo-elastic, thermo-elasto-plastic and creep deformations in CANDU fuel. The calculated bias and uncertainty from the validation activities confirms that FEAST 3.0 can be used with confidence for intended applications.

Within the prescribed domain of applicability, FEAT 4.0 is suitable for use in modelling the steady-state and transient heat flows in CANDU fuel, under conditions such as temperature-dependent thermal conductivity, flux depression, end flux peaking, non-uniform boundary conditions, and time-dependent boundary conditions. The calculated bias and uncertainty described in this report confirms that FEAT 4.0 can be used with confidence for intended applications.

7. REFERENCES

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