# VALIDATION OF FACTAR 2.0 AGAINST SMALL OUT-OF-PILE LABORATORY TESTS

C.J. WESTBYE, R.C.K. ROCK[1], L. SIE[2] AND G.R. BERZINS

Code Support & Model Development Section
Ontario Power Generation
700 University Avenue
Toronto, Ontario, Canada M5G 1X6

[1] Candesco Research Corporation
250 Dundas Street West, Ste. 600
Toronto, Ontario, Canada M5T 2Z5

[2] Universite Laval
Departement de genie mecanique
Laboratoire de robotique
Pavillon Adrien-Pouliot
Sainte-Foy, Quebec
G1K 7P4

## ABSTRACT

The Validation Plan for FACTAR 2.0 identifies the CHAN Thermal-Chemical Experimental Program, and in particular the three tests that used full-scale 28-element bundle simulators, as providing relevant experimental results for primary phenomena which are within the problem domain of FACTAR. Particular phenomena that are of interest in FACTAR validation are sheath-to-coolant and coolant-to-pressure tube heat transfer, channel and subchannel flow effects, pressure tube-to-calandria tube heat transfer, pressure tube oxidation, and element-to-pressure tube radiative heat transfer.

The specific tests identified used Fuel Element Simulators in order to represent the fuel bundle in an out-of-pile experimental facility. FACTAR 2.0 uses ELOCA-IST to represent the thermal-mechanical behaviour of fuel elements, which is not applicable to the Fuel Element Simulators. Therefore, a Fuel Element Simulator model was created, extensively tested, and incorporated into FACTAR.

This paper describes the testing performed on the Fuel Element Simulator model and the methodology for using the results from the CHAN tests in the validation of FACTAR

## INTRODUCTION

The Canadian Nuclear Industry has, over the past several years, implemented a formal framework for validation of computer simulation codes. At the highest level is the Technical Basis Document (TDB) [1], which describes the accident scenarios of interest to safety analysis of CANDU reactors. Included in the TBD are the key phenomena associated with each accident and their expected range of variation. The phenomena identified in the TBD are described in detail in the Validation Matrix documents for each major discipline of safety analysis. The Validation Matrix documents link each phenomenon to experiments that either directly or indirectly measure them.

For each major simulation code, Validation Plans were prepared which considered the phenomena represented by the code and, with reference to the appropriate discipline-specific Validation Matrix, identified experiments which would provide quantitative comparison data.

The FACTAR (Fuel And Channel Temperature And Response) code represents the thermal and mechanical behaviour of components within a CANDU fuel channel. These components include $UO_2$ fuel pellets contained within Zircaloy-4 sheaths, arranged in some fashion to form a fuel bundle, as well as the Zr-2.5wt% Nb pressure tube and Zircaloy-2 calandria tube. FACTAR calculates the thermalhydraulic response of the coolant resulting from postulated loss of coolant accidents coincident with changes in fuel power. Detailed modelling of the fuel element is performed by the ELOCA-IST code [2] which is embedded within FACTAR.

The problem domain of FACTAR described above is included in the Fuel and Fuel Channel Validation Matrix (F&FC VM) [3]. The phenomena that FACTAR models, with the identifier assigned in the F&FC VM, are [4]:

- fission and decay heating (FC1)
- diffusion of heat in fuel (FC2)
- fuel-to-sheath heat transfer (FC3)
- fuel-to-endcap heat transfer (FC4)
- fission gas release and pressurization (FC5)
- sheath deformation (FC6)
- sheath failure (FC7)
- fuel deformation (FC8)
- sheath oxidation (FC9)
- fuel or sheath melting (FC11)
- sheath-to-coolant and coolant-to-pressure tube heat transfer (FC13)
- channel and subchannel flow effects (FC14)
- pressure tube-to-calandria tube heat transfer (FC16)
- calandria tube-to-moderator heat transfer (FC17)
- pressure tube deformation (FC18)
- pressure tube oxidation and hydriding (FC20)
- element-to-pressure tube radiative heat transfer (FC21)

A large number of these phenomena are modelled by ELOCA-IST. Since ELOCA-IST is being validated independently, these phenomena do not need to be validated as part of FACTAR. The validation of the FACTAR code is focused on those phenomena that are related to the fuel channel rather than the fuel elements: FC13, FC14, FC16, FC17, FC18, FC20 and FC21.

The most relevant experiments which include these phenomena are full channel, out-of-pile tests. Of these experiments, the CHAN Thermal-Chemical experimental program [5, 6, 7] provide the best integrated data for qualification of the FACTAR code.

## CHAN THERMAL-CHEMICAL EXPERIMENTAL PROGRAM

As described in detail in the Fuel and Fuel Channel Validation Matrix [3], the test program was initiated at Whiteshell Laboratories, under COG Working Party 4, in the early 1980s. The program consists of several phases of experiments ranging from single fuel-element geometries, to 7-element and finally to full-scale 28-element geometries. These small-scale, out-of-pile tests were conducted in the High Temperature Heat Transfer Laboratory. The objective of these experiments was to provide a database of experimental results to assess the capability of various fuel channel codes to predict the thermal-chemical behaviour of the fuel channel under LOCA/LOECI conditions when the internal coolant is superheated steam at a very low, constant channel pressure.

The first phase of experiments (4 tests) involved single elements at low temperature (< 1500°C). The second phase of experiments (3 tests) involved a single element at high temperature (>1500°C). These two phases of experiments were carried out using a vertical test section. The purpose of these single-element tests was to provide a database to assess the convection and radiation heat transfer models (low temperature series) and the Zircaloy/steam reaction (high temperature series) in a simple geometry. In the third (3 tests) and fourth (4 tests) phase of experiments, designed to produce relatively low and high temperatures respectively, 7-element Fuel Element Simulators (FESs) were used to represent a multi-rod geometry. The purpose of the 7-element experiments was to provide a database to assess the subchannel radiation and convection models as well as the characterization of entrance hydraulic losses and flow distribution models. In the fourth phase, two experiments were performed in a horizontal configuration to study the effect of orientation and the effect of flow bypass on the thermal-chemical response of the test section.

The fifth phase of experiments (3 tests) used a 28-element geometry in a horizontal configuration, representing a typical CANDU fuel channel assembly. The purpose of these experiments was to provide a database to assess the capability of codes to simulate the thermal-chemical behaviour of a multi-ring fuel bundle and surrounding pressure tube when the internal coolant is superheated steam.

Validation of FACTAR is being performed using the three tests in the fifth phase 28-element geometry data sets. These tests are designated as Tests CS28-1, CS28-2 and CS28-3.

The heated length of the test section (1800 mm) was instrumented at various axial segments. CS28-1 used 80 thermocouples to monitor the temperatures of the test section: 37 inside the various FESs; 25 on the outer surface of the pressure tube; 11 on the outer surface of the calandria tube; 6 in the FES bundle flow subchannels; and 1 in the steam outlet line. CS28-2 used 94 thermocouples to monitor the temperatures of the test section: 48 inside the various FESs; 26 on the outer surface of the pressure tube; 13 on the outer surface of the calandria tube; 6 in the FES bundle flow subchannels; and 1 in the steam outlet line. Relative displacement of the pressure tube with respect to the calandria tube was monitored by top and bottom linear variable differential transformers (LVDTs). CS28-3 used 96 thermocouples to monitor the temperatures of the test section: 48 inside the various FESs; 28 on the outer surface of the pressure tube; 12 on the outer surface of the calandria tube; 7 in the FES bundle flow subchannels; and 1 in the steam outlet line.

The raw data was collected on a COMPAQ 386 personal computer using an OS/2 version of Labtech Notebook. The total power supplied from the power supply was recorded using an IBM AT personal computer running a DOS version of Labtech Notebook.

The following parameters against time were recorded for the period of the transient:

- power
- pressure
- steam flow rate
- FES temperatures
- steam temperatures
- flow tube/pressure tube temperatures
- calandria tube temperatures
- cooling water temperatures
- displacement
- hydrogen production

In each of the three tests (CS28-1 through CS28-3), the general test procedure involved at least three major phases (test CS28-2 had four). The phases common to all three tests were a steady-state, low power period, a period of increases-and-holds in power, and a high temperature, zero power oxidation period.

The data is well qualified and uncertainties calculated and documented in References 5, 6 and 7.

## MODELING WITH FACTAR

The use of Fuel Element Simulators (FESs) in place of fuel bundles causes a difficulty for FACTAR. Each FES consists of a graphite core with an electrical current passed through it to generate heat. An electrically-insulating layer of alumina surrounds the graphite, and the assembly is clad with a Zircaloy-4 sheath to mimic the external characteristics of a fuel element. ELOCA-IST is not able to represent this system. Therefore, a Fuel Element Simulator model had to be created and implemented into FACTAR in order to represent the experimental conditions.

The FES model needed to be able to:

- calculate the radial temperature distribution within each of the three regions, assuming good contact between regions;
- consider oxidation of the Zircaloy surface and the consequent heat generation;
- take the FACTAR-calculated convective heat transfer coefficient and radiant heat flux as boundary conditions, along with the specified heat generation rate; and
- allow for variable nodalization to permit grid-independence tests.

This model was implemented as a number of Fortran routines, encapsulated in a MODULE to enforce data hiding and object-oriented design. The thermal model solves the finite difference form of the one-dimensional heat conduction equation using a tri-diagonal matrix algorithm; this model was adapted from the thoroughly tested and validated model included in ELOCA-F. The sheath oxidation model is FROM3 [8] (or, based on user-input, one of the kinetic correlations incorporated in FACTAR).

Note that the version of FACTAR used in validation, 2.0b12, contains both the ELOCA-IST model and the FES model; the user selects which model to invoke. This means that the same code version used in safety analysis was used to perform the validation exercises. Since none of the phenomena being validated against the CHAN Thermal-Chemical test series are related to the fuel model, this is a direct validation of the constituent models in the remainder of the code.

To ensure that the FES model was correct, it was first tested as a stand-alone program against a variety of analytical problems and against data from the CS28-1 test itself.

The test cases first considered the radial temperature distribution through the three-region composite element, compared to an analytical solution obtained assuming constant thermal conductivity in each region. A variety of heat generation rates, thermal conductivities and nodalizations were considered. In each case the FES model performed very well, predicting results that agreed with the analytical solution to within better than 1°C. Figure 1 shows a sample result from this test series.

Transient predictions were tested in two ways. Stylized test cases were defined that used a very high thermal conductivity so that the system could be represented using a lumped-capacitance analytical solution. This test series used a simplified correlation for heat capacity that was a function of temperature, so that the effect of temperature-dependent properties could be assessed.

Again, excellent results were obtained, with maximum errors of about 3°C or 0.3%. Figure 2 shows these results.

The second transient test compared the results of the FES model, run using nominal thermal properties, to those predicted by the commercial Finite Element Modeling package ANSYS, version 5.5. The agreement with ANSYS was excellent, with less than 0.04° error; this result is shown in Figure 3.

As a final test, the FES model was driven with measured boundary conditions from an actual test, CS28-1. This comparison is shown in Figure 4. The agreement is seen to be very good, with a maximum difference about 20°C during the high-temperature portion of the transient. Such a difference can readily be accounted for by measurement uncertainties in the applied boundary conditions or in the measured temperatures themselves.

The above tests provide strong confidence that the FES model correctly implements and solves the governing equations for heat conduction in the three-region geometry. Use of this model is therefore expected to accurately capture the thermal response of the Fuel Element Simulators used in the CHAN test series.

## FACTAR VALIDATION METHODOLOGY

The experimental geometry was defined using input files to FACTAR. One-eighth symmetry was assumed for each bundle. In each test, there was one unpowered element which challenges this symmetry assumption. Sensitivity studies were performed (*i.e.*, averaging the total ring power uniformly across each ring or assuming the powered element was actually producing energy) to assess the impact of this assumption.

Parameters measured during each test were used to define channel boundary conditions. The required boundary conditions are steam inlet enthalpy, inlet flow rate, steam pressure and the fuel power throughout the test. These conditions are all available (or can be calculated) from the measured data.

For each test, a base case was defined. Each base case consists of the best estimate for each boundary condition, plus particular modelling assumptions. These modelling assumptions include the reference FES oxidation model, the reference pressure tube oxidation model, the treatment of the power boundary condition for the unheated element or when the ring-to-ring power ratio fluctuates, and the reference coolant mixing model. Sensitivity studies were performed from the base case by varying boundary conditions within their uncertainty bounds, and by changing the modelling assumptions.

Validation of FACTAR using this methodology is currently ongoing.

## CONCLUSIONS

This paper has summarised the approach to validating FACTAR using data from the CHAN Thermal-Mechanical experimental program tests CS28-1, CS28-2 and CS28-3. The focus of the validation is on the thermalhydraulic conditions within a fuel channel populated with simulated 28-element fuel bundles. These conditions include convective and radiative heat transfer and flow mixing and bypass. Other phenomena that are applicable for FACTAR validation include Zircaloy oxidation and pressure tube heat up and deformation.

A key requirement for modelling these tests is the implementation of a Fuel Element Simulator model into FACTAR. The development and testing of this model has been described.

Preliminary results, not presented in this paper, show that FACTAR is able to capture the measured results from these tests within the measurement uncertainty. In turn, this implies that the primary phenomena listed above and their interactions are well represented by the FACTAR code.

## REFERENCES


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**FIGURE 1**
**Steady-state Heat Conduction Equation**
**Analytical versus Numerical Results**
**Bundle Power = 40 kW**
**Outer Ring power factor = 1.111**

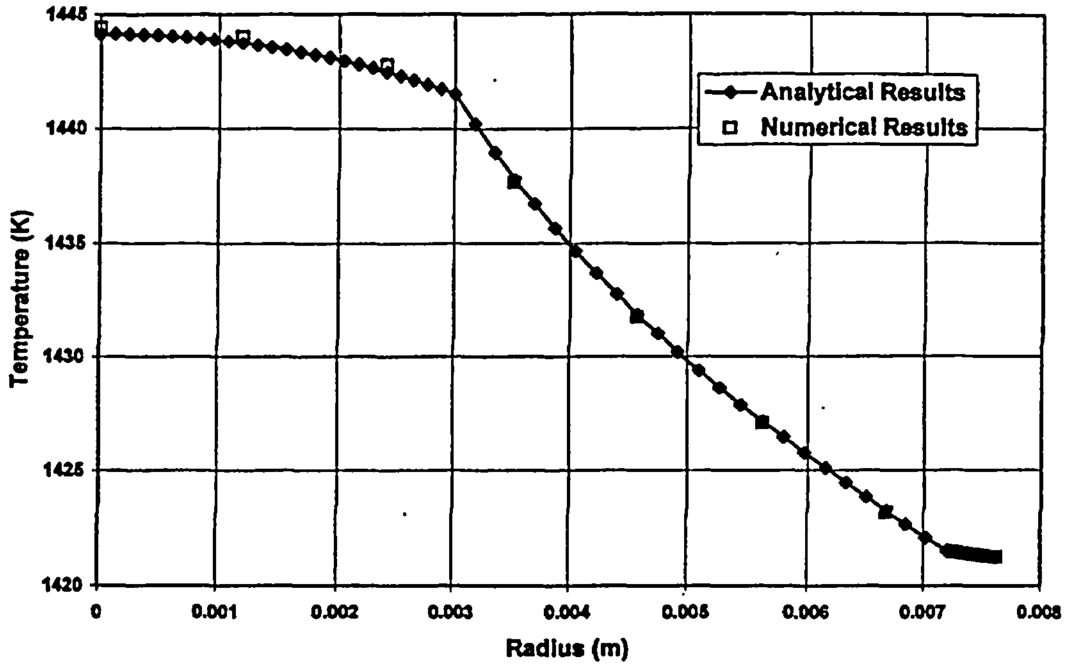


**FIGURE 2**
**Lumped-capacitance transient**
**Temperature-dependent heat capacity, constant heat generation**

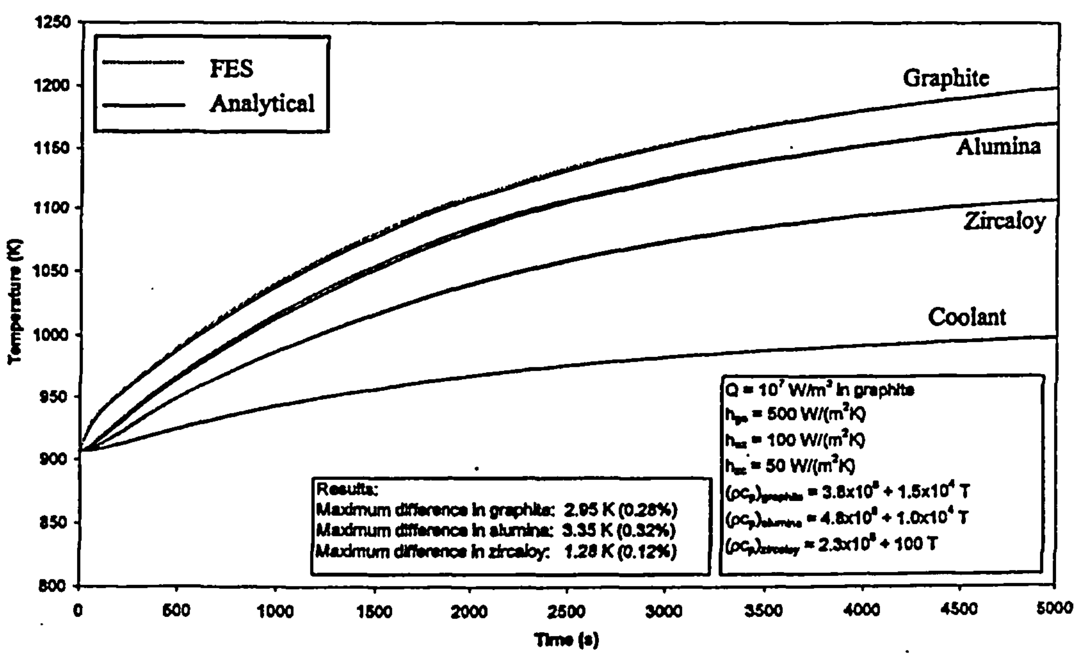

**FIGURE 3**

**FES Model Code versus ANSYS Transient Results**

**Outer Sheath Node Comparison**

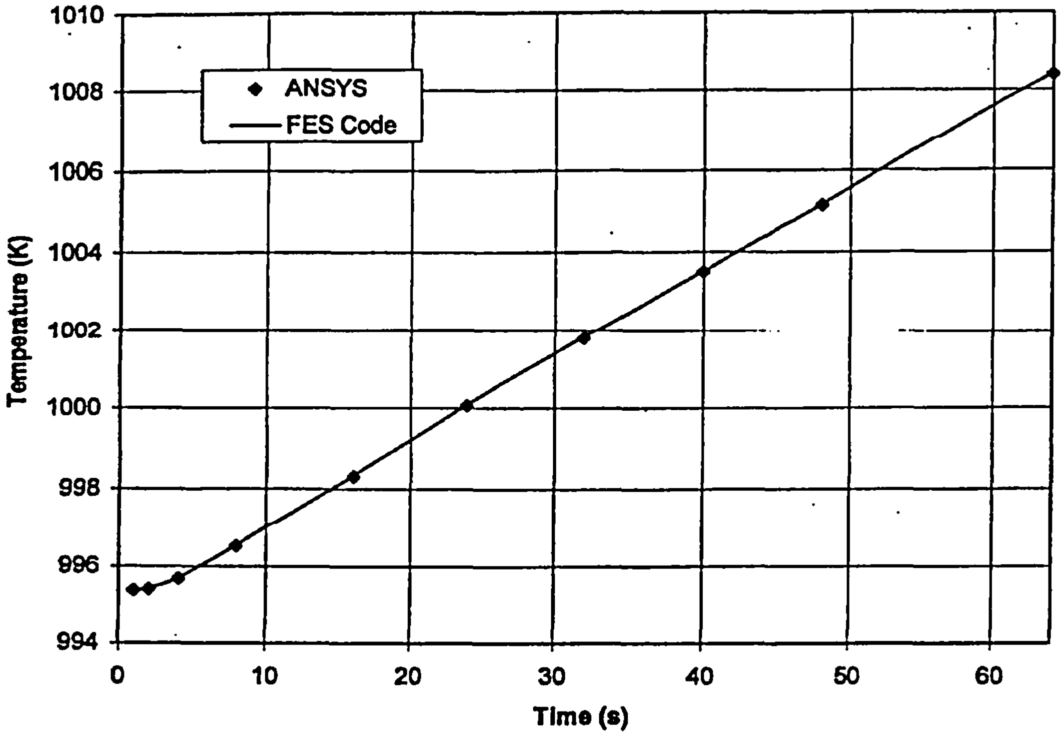


**FIGURE 4**

**CHAN Experiment Results versus FES Model Code Results**

$T_{coolant} = 863$ K

$H_{s} = 43.27$ W/(m$^2$K)