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ABSTRACT:

The reactivity initiated accident CIP0-1 test was performed with UO2 high burnup fuel (75GWd/tU) with Zirlo cladding in the CABRI sodium loop facility, at 280°C and low pressure (~3 bars). No boiling crisis and no failure of the fuel rod occurred during the test. This paper presents the SCANAIR and BISON codes computation results versus experimental data obtained on CIP0-1 test for the Pellet Clad Mechanical Interaction phase, first stage of a reactivity initiated accident.

The initial state of the rod calculated by irradiation codes are compared with measurements before the transient. Then global rod thermal behavior during the CIP0-1 test is assessed with the sodium coolant temperature measurements. The rod mechanical behavior analysis is based on the fuel and clad elongation and the clad residual hoop strain. Finally, the fission gas behavior predicted by the SCANAIR and BISON codes is compared to the measurements of the fission gas released in the experiment.

KEYWORDS: *SCANAIR code, BISON code, RIA power transient, benchmark, PCMI.*

I. INTRODUCTION

In the frame of their respective research programs on fuel safety, the French “Institut de Radioprotection et de Sûreté Nucléaire” (IRSN) and the “Idaho National Laboratory” (INL) have respectively developed the SCANAIR (Ref. 1, Ref. 2) and BISON (Ref. 3) codes to describe the thermo-mechanical behavior of irradiated fuel rods during Reactivity Initiated Accidents (RIA) in Light Water Reactors (LWR).

A RIA, characterized by a very rapid increase of reactivity and power in some rods of the reactor, can be schematically represented in two main phases. First, the energy deposition leads to a rapid rise of the fuel temperature which induces thermal swelling of the fuel pellets. During this phase, the Pellet Clad Mechanical Interaction (PCMI) leads to clad deformation and potentially to failure depending on the fuel enthalpy increase and on the level of clad embrittlement.

After the PCMI phase, the increase of clad temperature can lead to the boiling crisis of the water surrounding the rod. During the film boiling phase, the clad to coolant heat transfer becomes very low and the clad can reach high temperature (>700°C). Depending on the internal gas pressure, the ductile clad can undergo large deformation and possible failure. The RIA codes have to predict properly these two phases of the transient in order to be used, in particular, for the assessment of current fuel safety criteria but also to be able to predict the behavior of upcoming fuel such as accident tolerant fuel.

The objective of this paper is to compare BISON, a generic fuel code recently adapted for RIA transient, with SCANAIR, a code dedicated to RIA power transient. The SCANAIR V_7_7 and BISON 1.3 codes computation comparisons against experimental data obtained on CIP0-1 test are presented for the first stage of the transient, the PCMI phase. The CIP0-1 experiment was performed with UO_2 high burnup fuel (75GWd/tU) with Zirlo cladding in 2002 in the CABRI sodium loop facility, at 280°C and low pressure (~3 bars). No boiling crisis and no failure of the fuel rod occurred during the test.

After a brief description of CIP0-1 test conditions and results, the initial state of the rod calculated by irradiation codes are compared with measurements performed before the transient. Then global rod thermal behavior during the CIP0-1 test is assessed especially with the sodium coolant temperature measurements. The rod mechanical behavior analysis is based on the fuel and clad elongation and the clad residual hoop strain. Finally, the fission gas behavior predicted by the SCANAIR and BISON codes is compared to the measurements of the fission gas released in the experiment.

II. CIP0-1 ROD CHARACTERISITICS BEFORE THE TRANSIENT

The CIP0-1 rodlet was refabricated from the fifth span of an ENUSA fuel rod irradiated in the Pressurized Water Reactor (PWR) Vandellos 2 in Spain in the frame of a joint Japanese-Spanish R&D program aimed at studying the behavior of UO_2 fuel at high burnup (Ref. 4, Ref. 5). The UO_2 rod, with an initial Uranium 235 enrichment of 4.5% and a Zirlo cladding, has been irradiated for 5 cycles, from June 1994 up to September 2000, until a rod average burnup of 68 GWd/tU.

The SCANAIR input data deck is resulting from end-of-life state calculated by FRAPCON V4.0 code (Ref. 6) for the whole rod. BISON was used for both the base irradiation and the RIA simulations, the same geometry, CIP0-1 rodlet, was then modelled for both simulations.

The burnup distribution measured and calculated by the irradiation codes along the rod are represented in Fig. 1. The maximum local burn-up was 77 GWd/tU. The rod average burnup for the CIP0-1 section calculated by FRAPCON and BISON was respectively 75.0 and 75.3 GWd/tU.

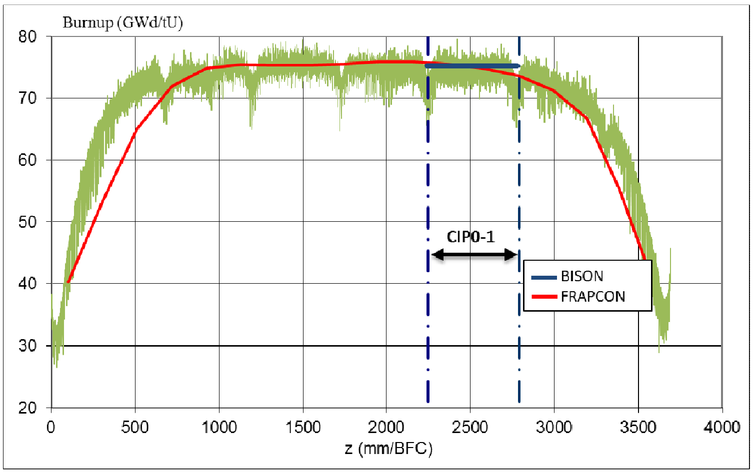

Fig. 1. Axial profile of burnup of CIP0-1 mother rod, measurements vs FRAPCON and BISON calculations.

The examinations performed on the entire rod after irradiation in the Swedish Studsvik laboratory have shown the following results:

- rod axial elongation of about 0.8%
- fissile column axial elongation of 0.93%
- fission gas release in the free volume : 7.4% of the total fission gas created during the irradiation
- free volume : 12.26 cm^3
- plenum pressure : 5.85 MPa at 0°C

The rod refabrication and some non-destructive examinations on the rodlet were performed in the Studsvik laboratory. The length of CIP0-1 test rod was 541 mm. The diameter measurements and zirconia thickness on the outer part of the clad are represented in Fig. 2. The clad oxidation was significant: the mean zirconia thickness was 80 µm, varying between 50 and 110 µm over the length of the sample. The oxidation level at CIP0-1 rod location is rather well predicted by both irradiation codes. There is a good agreement between measurements and BISON calculation for the clad outer diameter at span 5. For FRAPCON the clad diameter was overestimated.

Some destructive exams performed on span 6 of the mother rod showed that the rod was highly hydrided (see Fig. 3, left), with a mean hydride concentration of about 1000 ppm. The hydrides were long and oriented in the circumferential direction. No hydride blisters were found but hydride rims with a thickness of 50 µm were present. On fuel examinations, one can estimate the visible rim width to be about 120 ± 30 µm (probably corresponding to fully restructured rim). It's also worth noticing the very tight bonding between fuel and inner zirconia layer (Fig. 3, right).

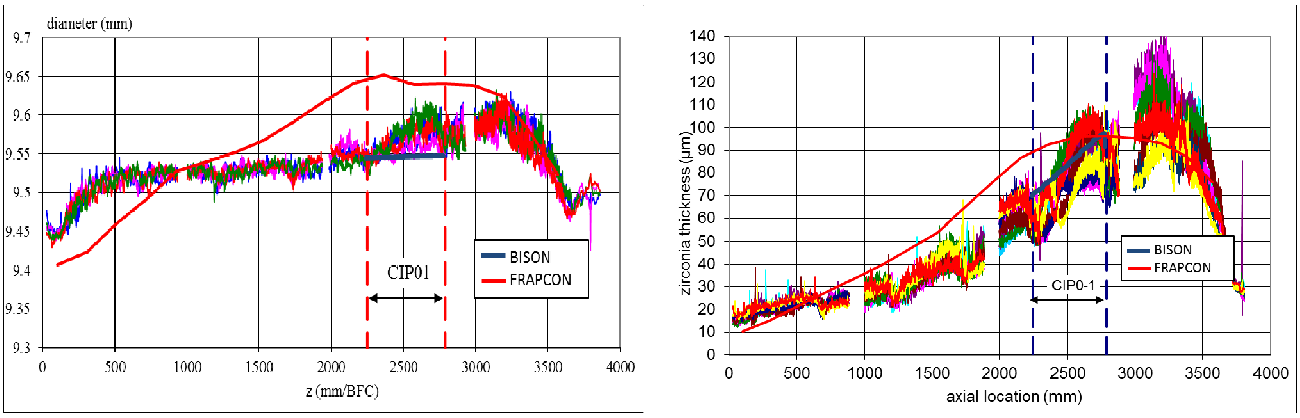

Fig. 2. Axial profile of CIP0-1 father rod diameter (left) and oxide thickness (right), measurements vs FRAPCON and BISON calculations

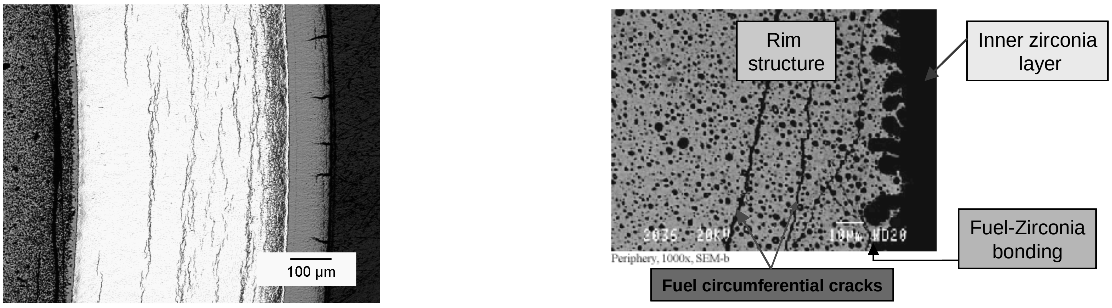

Fig. 3. Optical micrograph of the cladding (left), SEM examinations of polished surface in the fuel outer part (right)

III. CIP0-1 TEST CHARACTERISITICS AND RESULTS

III.A. CIP0-1 Test characteristics

The CABRI CIP0-1 test was performed in 2002 in the sodium loop of the CABRI facility (CEA Cadarache). The main characteristics of the power transient were (see Fig. 4):

- Maximum core power : Pmax=3692 ±222MW
- Core energy deposition: Ecore = 189.6 ±11.4MJ (1.2s after the beginning of the energy deposition)
- Power pulse width at half maximum: 32.4 ±0.5ms
- Injected energy in the test rod at peak power node (PPN): ε_{PPN}=99±6 cal/g (1.2s after the beginning of the energy deposition)

According to the measurements performed during and after the test, the rod underwent the power transient without clad failure.

II.B. CIP0-1 test results

The visual examinations confirmed the non-failure of the rod and showed the high oxide spallation of the rod along all the angular orientations with many spalled areas (see Fig. 5, white area) of large dimensions (several mm wide and often several cm long). The oxide spalling phenomenon is also noticeable on the clad diameter and zirconia thickness measurements that were performed along 4 and 8 azimuths, respectively.

The direct comparison between raw clad diameter measurements before and after test does not allow to estimate the clad residual hoop strain. The clad diameter measurements have been corrected based on the zirconia thickness measurements before and after test (see Fig. 6) in order to calculate the sound clad diameter before and after test and thus the clad residual hoop strain. The clad residual hoop strain ranges between 0%, at both extremities of the rod, to 0.5 ±0.1% at the PPN location. According to the rod puncturing, the fission gas release was estimated to be 13-16 % of the creation and the final free volume pressure at 20°C was 29 ± 22.6 bars.

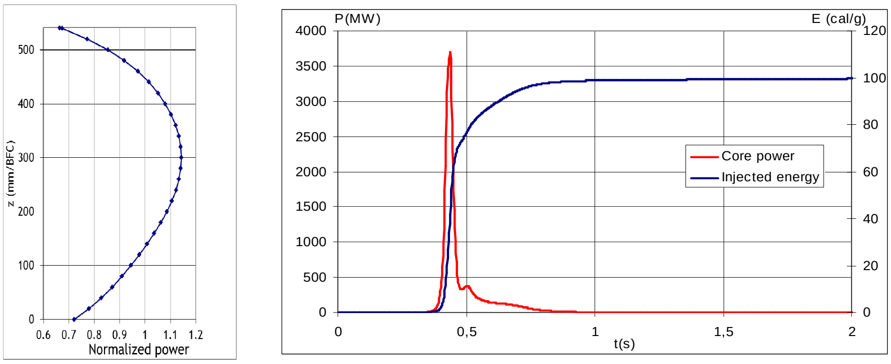

Fig. 4. Axial power profile (left); Core power and injected energy during the CIP0-1 test (right)

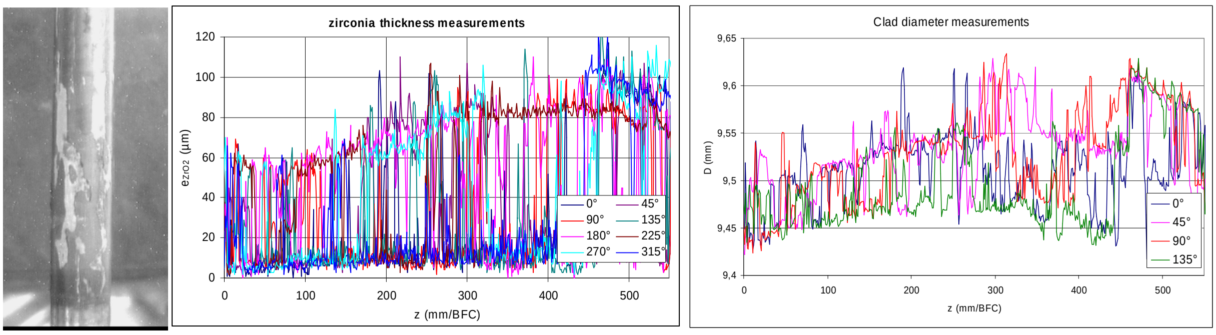

Fig. 5. visual examination of the rod after test (left), zirconia thickness (middle) and clad diameter measurements (right)

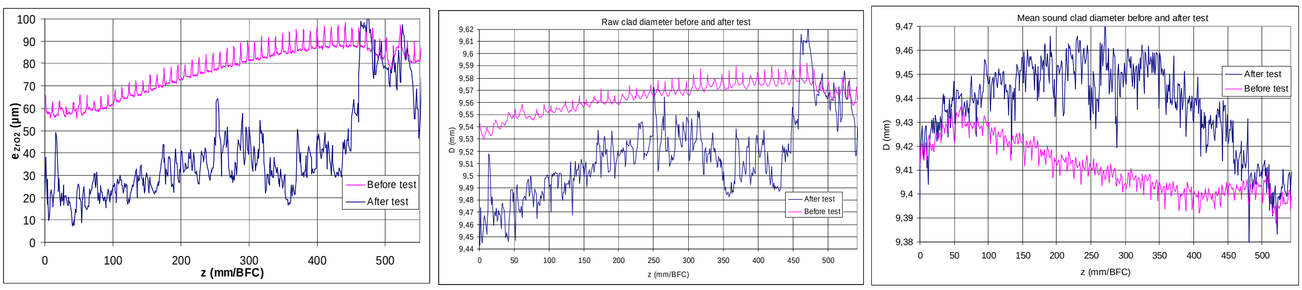

Fig. 6. Zirconia thickness measurements before and after test (left), raw clad diameter measurements before and after test (middle) and corrected diameter measurements before and after test

IV. SCANAIR AND BISON CALCULATIONS

IV.A. SCANAIR input data and hypotheses

SCANAIR is a so-called "1.5D" code dedicated to the simulation of fast power transients in LWR. It is designed to model a single rod surrounded by a coolant channel and possibly limited by an external shroud. To describe properly the complex phenomena occurring during fast power transients, SCANAIR takes into account the following physical phenomena and their strong coupling: thermal dynamics including clad-to-coolant heat transfer modeling in sodium or water conditions, structural mechanics for the rod constitutive elements, and fission gas transient behavior. SCANAIR is thus a set of three main modules dealing with thermal dynamics (including thermal-hydraulics in the coolant channel), structural mechanics and gas behavior. These modules communicate with each other through a database. An external module to the three main modules is devoted to evaluate the risk of clad failure during the transient thanks to several failure models.

A schematic view of the SCANAIR general processing is shown in Fig. 7.

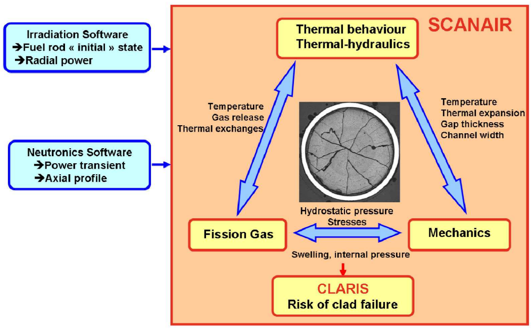

Fig. 7: Schematic view of the SCANAIR general processing

<u>Hypotheses for CIP0-1 test calculation</u>

The initial rod state (rod geometry, porosity and gas distribution, local burnup, etc...) is extracted at the CIP0-1 rod location from the FRAPCON calculations on the whole rod using a dedicated interface.

<u>Geometry and mesh</u>

- Geometry: as observed on exam in Fig. 3, the fuel and the clad are bonded with the creation of an inner zirconia layer at high burnup; the fuel outer radii were adjust to have a fuel clad gap equal to 2µm at 20°C and then a closed gap before the transient at 280°C.
- Fuel mesh: the three FRAPCON axial meshes, corresponding to the CIP0-1 rod location (fifth span), were each divided in five parts in order to perform SCANAIR calculations with 15 axial meshes (each axial slice contains about 4 pellets). The FRAPCON radial fuel mesh is composed of 16 equi-volume radial meshes. In order to obtain a better description of the transient behaviour especially in the rim area, the three outer meshes were divided respectively in 2, 3 and 5 leading to 23 radial meshes in the SCANAIR calculation.
- The clad is divided in 7 radial meshes: five equi-volume meshes for the sound clad and two meshes for the zirconia layer.

<u>Zirconia thickness</u>

Pre and post-test examinations have shown a partial spalling during the transient. The hypothesis was done that this phenomenon occurred at the very beginning of the transient. The SCANAIR calculation was performed considering the averaged zirconia thickness measurements after test: that is to say 23 - 36 – 59 µm for the three FRAPCON meshes.

<u>Hypothesis for the fuel microstructure</u>

- According to the metallographic exam, a fuel outer rim width of 100µm has been considered.
- The fuel porosity is fixed at 5% except in the rim area where it reaches 15%.

Mechanical modelling

- Fuel mechanical behaviour: elastic plus perfectly plastic behavior with fuel yield stress depending on temperature.
- Clad mechanical behaviour: anisotropic Lemaitre formulation, modelling the viscoplastic behaviour within the whole range of temperature range (Ref. 1).
- The fuel grain boundary failure limit is fixed at 50 MPa.
- The sticking option is used: when the fuel clad gap is closed the fuel and clad axial displacements on the boundary are identical.

Fuel to clad heat exchange

The outer fuel rugosity is supposed to be very low (0.1µm) to model a quasi-perfect fuel-clad heat exchange that is especially the case when the fuel is bonded to the cladding after creation of an inner zirconia layer (see Fig. 3).

IV.B. BISON input data and hypotheses

BISON is a nuclear fuel performance code that has been under development at Idaho National Laboratory (INL) since 2009. BISON is a parallel, finite element-based tool that solves the coupled non-linear partial differential equations associated with nuclear fuel behavior. The code is applicable to both steady and transient fuel behavior and is used to analyze 1D spherical (1.5D capabilities recently added), 2D axisymmetric, or 3D geometries and uses implicit time integration, important for the widely varied time scales in nuclear fuel simulation. BISON is intended to be a multi-fuels code. Though primarily applied to LWR fuel to date, the code has been used to analyze TRISO-coated particle fuel and metal fuel in rod and plate.

BISON is built using the INL Multiphysics Object-Oriented Simulation Environment, or MOOSE. MOOSE is a massively parallel, finite element-based framework to solve systems of coupled non-linear partial differential equations using the Jacobian-Free Newton Krylov (JFNK) method. This allows modelling of large, computationally expensive problems from a full stack of discrete pellets in a LWR fuel rod up to every rod in a reactor core.

The BISON governing relations currently consist of fully-coupled partial differential equations for energy, species, and momentum conservation. Users can select a subset of these equations (e.g., energy and momentum for thermomechanics analysis) within the input file. The code employs both non-linear kinematics, which accounts for large deformation, and nonlinear material behavior.

Hypotheses for CIP0-1 test calculation

Geometry and mesh

BISON was used for both the base irradiation and the RIA simulations. The same geometry, CIP0-1 rodlet, was modelled for both the base irradiation and the RIA simulations. The rodlet was modelled using a 2D-axisymmetric mesh with 11 equally spaced quadratic elements in the fuel and 4 elements in the cladding. The zirconia layer is not directly meshed but its thickness and thermal impact is tracked numerically in the code. The fuel was separated into 220 axial elements (4 per pellet) and the cladding had a similar axial element size as the fuel.

The fuel clad gap during cold conditions after the base irradiation was 18µm and that gap reduced to 14µm at hot conditions before the transient.

Zirconia thickness

One of the benefits of BISON performing both the base irradiation and the RIA is that all of the nodal and elemental variables are carried over from base irradiation into the transient. The end of base irradiation calculations for the clad diameter and oxide thickness depicted in Fig. 2 are the same initial conditions for the RIA. No spalling was considered in the RIA simulation.

Hypothesis for the fuel microstructure

BISON does not have a high burnup fuel microstructure model so the fuel grain radius and porosity fraction were held constant at 5µm and 4.3%, respectively.

Mechanical modelling
- Fuel mechanical behaviour: elastic fuel behaviour.
- Clad mechanical behaviour: Zr4 creep model used during the base irradiation, isotropic plasticity model adapted for Zirlo cladding during the RIA.

Fuel to clad heat exchange
- Standard BISON LWR gap conductance model used during the base irradiation.
- Same model used during RIA with modified fuel rugosity (0.1 µm).

IV.C. Results

Thermal results

When assessing safety criteria for reactivity initiated accidents each regulatory body has different failure criteria. The U.S. Nuclear Regulatory Commission (USNRC) has stated that reactivity excursions cannot result in radial average fuel enthalpy greater than 1172 J/g (280 cal/g) at any axial location in any fuel rod (Ref. 7), but this limit is currently under review and being modified. In France the fuel enthalpy limit depends on the fuel burnup and the cladding type and is currently under discussion between the French nuclear utility, (EDF) and the French regulatory body (ASN). The ability to predict the fuel enthalpy accurately is then important for these codes.

The variation of fuel radial averaged enthalpy (from HZP conditions) at the peak power node (PPN) is plotted in Fig. 8 (left) and the fuel centerline temperature (right). The agreement between the two codes is good with slight variations occurring at the end of the pulse and during the cooling phase for both the radially averaged enthalpy and fuel centerline temperature. The max values for fuel radially averaged enthalpy are 76.59 and 76.65 cal/g for SCANAIR and BISON respectively both occurring between 0.71-0.72 seconds. The peak fuel centerline temperature is 1325°C at 1.89 seconds for SCANAIR and 1347°C at 2.05 seconds for BISON.

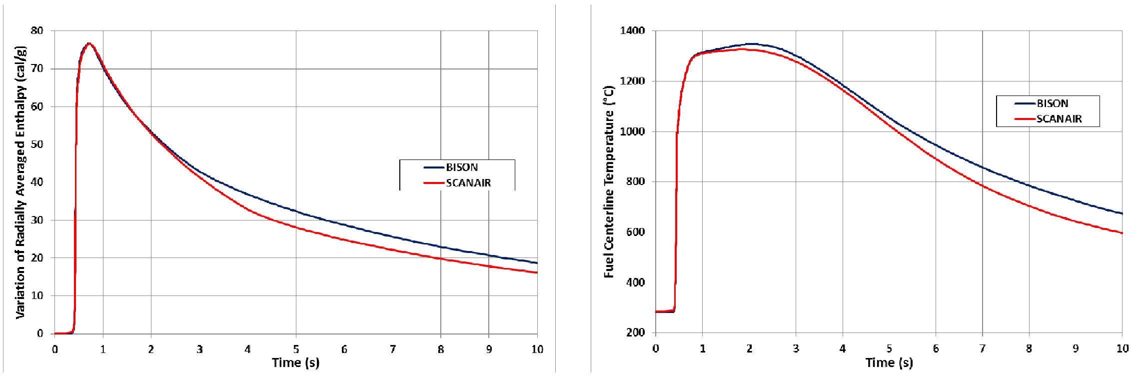

Fig. 8. Fuel Enthalpy and center temperature (PPN location)

Fig. 9 shows the fuel surface, clad inner and clad outer temperatures for SCANAIR and BISON as well as the fuel-to-clad heat transfer coefficient. The temperature comparison highlights considerable differences between the fuel outer surface temperatures with BISON predicting temperatures as high as 955°C compared to 700°C from SCANAIR. These differences can be explained by differences in the gap conductance models depicted in Fig. 10 (right). SCANAIR begins the simulation at hot conditions with a closed fuel clad gap greatly increasing the gap conductance where BISON begins with a 14µm gap that takes time to close. Even after the gap closes in BISON the gap conductance is still approximately 8 times smaller than predicted in SCANAIR. In spite of the large differences between the gap conductance and fuel surface temperatures the cladding inner temperatures are similar between the two codes. Similarly to the fuel outer temperature, the clad outer temperature is higher in BISON than SCANAIR.

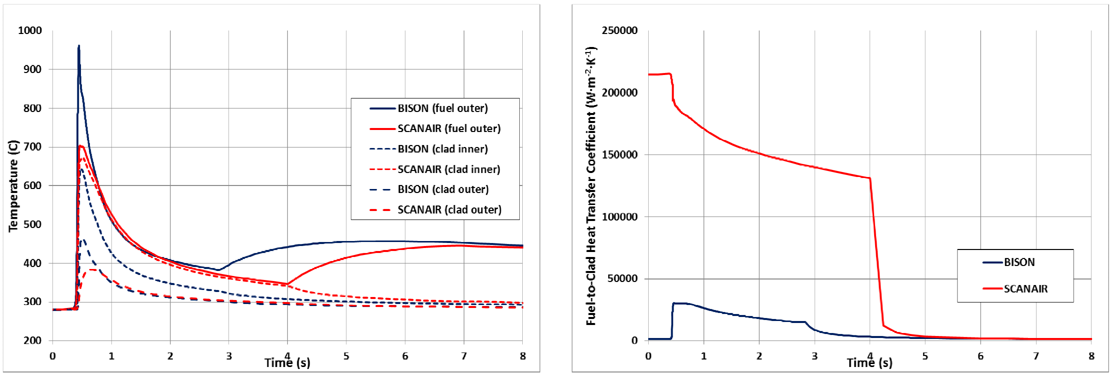

Fig. 9. Fuel outer, clad inner, and clad outer temperatures (left) and fuel-to-clad heat transfer coefficient (right) vs time (PPN location)

Fig. 10 shows the sodium coolant temperature measurements vs. SCANAIR and BISON calculations at 25 and 47 cm from the bottom of fissile column. The SCANAIR calculations are in very good agreement with the measured values during the test while the BISON results over predict the results considerably at the beginning of the transient. The higher coolant temperatures is likely one of the reasons for the higher clad outer surface temperature.

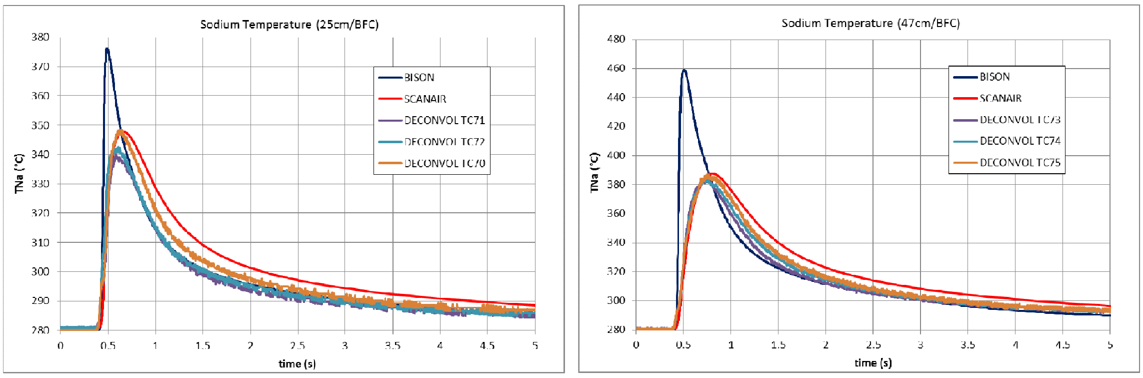

Fig. 10. Sodium temperature measurements vs. calculations at 25 cm/BFC and 47 cm/BFC

The large differences in the clad outer surface temperatures and sodium temperature calculations between the two codes can be due to numerous mechanisms. First the effect of oxide thickness and spallation is accounted for in the SCANAIR calculation whereas the BISON simulation tracks the oxide thickness and its effects on thermal resistance when used with water coolant but currently has no impact thermally when using the sodium coolant model. Second the sodium thermal hydraulic correlation is limited in BISON. Only the modified Schad correlation (Ref. 8) for fast breeder reactors is available and has not been tested or validated for the flow or transient conditions in the CABRI sodium loop. In SCANAIR the clad to sodium heat exchange coefficient is calculated using the Lyon's law.

Mechanical results

Whereas many of the thermal parameters are code to code comparisons due to the difficulty and limitations in measuring cladding and fuel temperatures, there are a few mechanical parameters that can be directly compared to experimental results. Fig. 11 shows the fuel and clad elongations with the experimental measurements of the cladding elongation. The two codes calculate very similar fuel axial elongation but due to current complications in modeling frictional contact in BISON the cladding axial elongation calculations are considerably different. SCANAIR employs a sticking option when the fuel and clad are in contact resulting in identical fuel and clad elongation during contact. The large change in fuel elongation at approximately 7 seconds is when the gap reopens between the fuel and the cladding negating the sticking option. SCANAIR is able to closely resemble the measured cladding elongation with slight deviations possible due to actual slipping between the fuel and the clad during the experiment. As mentioned previously, BISON strongly underestimate the cladding elongation as it uses a frictionless contact model and the only elongation seen is due to thermal expansion and Poisson effect from large radial displacements. The fuel elongation results in Fig. 11 are promising and with frictional contact the cladding elongation results could be improved similar to the SCANAIR results.

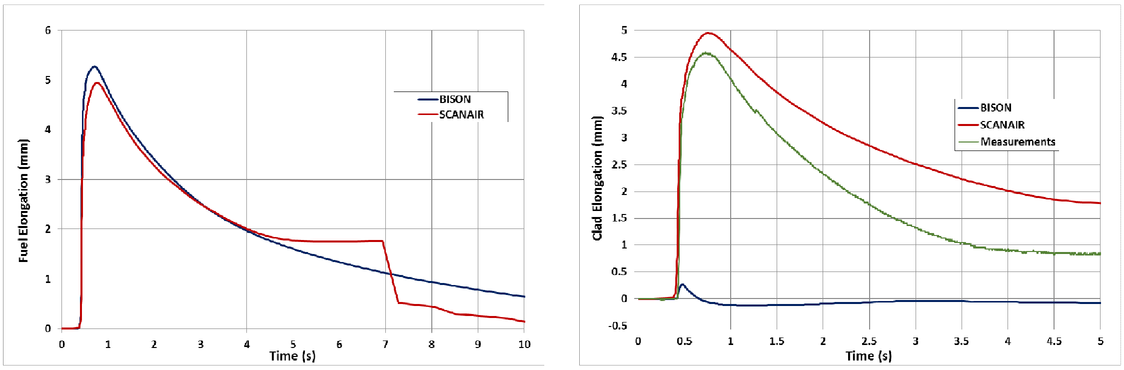

Fig. 11. Fuel and clad elongation vs time

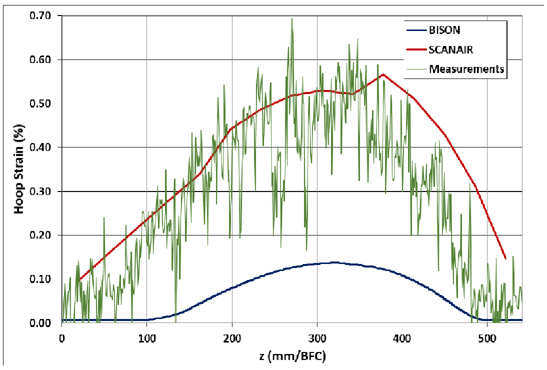

Fig. 12. Clad residual hoop strain

Post-test clad diameter measurements along the rodlet (Fig. 6) provide residual cladding hoop strain results to compare against. The SCANAIR and BISON comparisons against the experimental residual hoop strain is shown in Fig. 12. Similar to the cladding elongation, SCANAIR accurately calculates the residual cladding strains that are close to the measured results, whereas BISON greatly underestimates the residual strain in the cladding. The magnitude for the calculated cladding hoop stress (Fig. 13) is similar for both SCANAIR and BISON even though the total hoop strain is considerably lower with BISON.

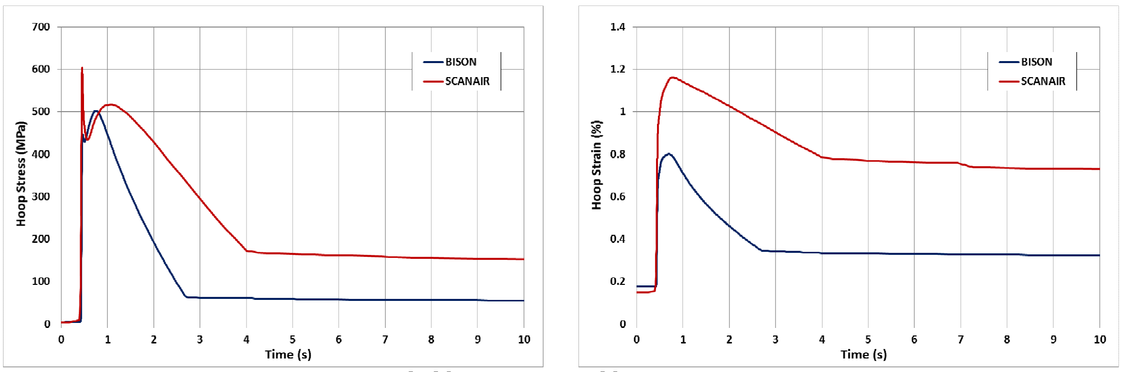

Fig. 13. Clad hoop stress and hoop strain vs. time

Many of the mechanical shortcomings apparent in BISON have origins from two main differences with SCANAIR. First is the large difference in fuel cladding gap prior to the transient. As mentioned previously, the BISON RIA simulation inherits its initial conditions from the BISON base irradiation simulation using the same geometry. The base irradiation assumed after cooling down that the fuel to cladding gap was 18µm that closed to 14µm at the beginning of the transient. In a RIA the cladding deformation is controlled by the rapid thermal expansion of the fuel into the cladding. Referencing from hot conditions just prior to the transient, the maximum fuel radial displacement calculated by SCANAIR is 55µm and 44µm in BISON. The maximum displacement at the inside of the cladding in SCANAIR is 55µm (same as the fuel) where in BISON it is just under 30µm. Assuming no initial gap and applying 14µm additional displacement to the cladding gives similar hoop strain estimations show in Fig. 13. The second difference is the difficulty in using frictional contact currently in BISON. Frictional contact will improve the cladding elongation calculations in Fig. 11. The residual strain plotted in Fig. 12 is mainly plastic strain accumulated during the RIA. In BISON frictional contact will increase the equivalent von Mises stress and results in more plastic yielding.

<u>*Fission gas release*</u>:

The fission gas release calculated by SCANAIR was 15% of the gas quantity in the fuel rod before the transient compared to the 13 to 16% measured after test. BISON calculated a 4.6% fission gas release after the base irradiation and during the RIA that fission gas released increased to 8%. With only the final fission gas release it was difficult to assess the global fission gas behavior during the transient.

V. CONCLUSIONS

The SCANAIR-BISON benchmark on the CIP0-1 RIA test has provided an opportunity to compare the results obtained from SCANAIR, a long-established and proven code specifically dedicated to modeling of fast transients, to BISON, which is just starting into development for RIA transients. This is the first application of BISON on a RIA transient of a pre-irradiated rod. The results from this benchmark have proven beneficial to BISON as it helps locate the areas of focus for future development of BISON for RIA and fast transient applications.

The calculations of CIP0-1 test performed in the sodium loop of CABRI reactor supports code assessment for the first stage of the transient, the PCMI phase. INL uses the BISON code for steady state and transient calculations, while IRSN evaluates the state of the rod before the transient with a FRAPCON code calculation and adjustment based on the experimental measurements done before the transient. The initial gap between fuel and cladding and the clad oxide thickness were thus significantly different between BISON 1.3 and SCANAIR V_7_7 calculations before the transient.

For the fuel thermal behavior during the transient, the differences in the estimation of fuel enthalpies and temperatures are rather limited especially for maximum values of these parameters. Concerning cladding and coolant temperatures, a substantial scatter is obtained. This scatter seems to be related to the heat exchange modelling between fuel and cladding and also to the clad oxide layer thermal insulation modelling.

The fuel thermal expansion is very similarly modeled in both codes. Nevertheless, due to the difference of the initial gap and the different modelling of the contact between fuel and clad during the PCMI phase (slipping for BISON and sticking for SCANAIR), there is a large difference on the clad elongation and hoop strain for the two calculations. The SCANAIR calculations are consistent with the clad elongation and clad hoop strain measurements.

The fission gas behavior had only little impact on this test with limited injected energy. Furthermore with only the final fission gas release it was difficult to assess the global fission gas behavior during the transient.

After this first step on the PCMI phase modelling, the collaboration and benchmarking between SCANAIR and BISON could continue for the film boiling phase modelling. Results of the upcoming tests in CABRI International Programme and tests in TREAT reactor will be very helpful for this future work.

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