ISP 28

OECD/NEA/CSNI
International Standard Problem N° 28

Phebus-SFD B9+ Experiment
on the Degradation of a PWR Type Core

COMPARISON REPORT

Volume 2

December 1992

COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS (CSNI)
OECD NUCLEAR ENERGY AGENCY
Le Seine Saint-Germain - 12, boulevard des Iles
92130 Issy-les-Moulineaux, France
RAPPORT TECHNIQUE SEMAR 92/82
NOTE PHEBUS CSD 92/134
OECD/NEA/CSNI/R (92) 17

INTERNATIONAL STANDARD PROBLEM N°28

PHEBUS-SFD B9 + EXPERIMENT
ON THE DEGRADATION OF A PWR CORE TYPE

Comparison report - Volume 2

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December 1992

*CEA/IPSN/DRS - CADARACHE
**CISI INGENIERIE - AIX EN PROVENCE

LABORATOIRE DE PHYSIQUE DES ACCIDENTS

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ABSTRACT OF VOLUME 2

This volume 2 of the ISP28 report contains the compilation of the 15 sets of code-to-data comparison plots submitted by the 15 different organizations which participate in the calculation of the PHEBUS-SFD B9+ test.

The final set of plots given in the Appendix 16, is devoted to code-to-code comparisons.
The Nuclear Safety and Protection Institute (IPSN) of CEA proposed the PHEBUS Severe Fuel Damage B9+ test as the basis for an OECD/CSNI International Standard Problem. The objectives of the test were to study the following main phenomena occurring during the early phase of an SFD accident in a PWR: cladding oxidation, the mechanical behaviour of cladding with a ZrO₂ layer of variable thickness containing molten zircaloy, the simultaneous dissolution of UO₂ and ZrO₂ by molten Zry and melts relocation. These phenomena being crucial for a description of fuel behaviour during severe accidents, the B9+ test was accepted with semi blind conditions as International Standard Problem ISP 28.

Measured thermal-hydraulic conditions were supplied to help participants to calculate rod thermal behaviour as correctly as possible in order to evaluate the capabilities of the codes to calculate bundle degradation (blind part) using the appropriate thermal conditions. The calculations could be performed using two kinds of radial Boundary Conditions: a constant temperature applied on the external cold surface of the shroud (1st approach) or temperature evolutions versus time at different levels of the internal surface of the shroud (2nd approach). The first approach needed a fine modelling of all the layers of the shroud, in particular of the porous ZrO₂ layer which mainly determines the shroud insulation. The second approach, which was proposed to avoid modelling of the shroud, was "code dependent" because the thermal conditions were defined by a best estimate ICARE2 calculation.

The results of 17 calculations were submitted by 15 different organizations from 12 countries. Eight different codes were used and 4 calculations were performed using the second approach.

The calculated results were compared to measurements performed during the transient (fluid, rod and shroud temperatures, H₂ release) and to the final state of the bundle deduced from Post Test Examinations measurements (cladding oxidation, UO₂ dissolution, cladding dislocation, relocation of molten materials, flow blockage, ...).

Two groups of calculations can be distinguished. The first were performed with SCDAP Mod1, SCDAP/RELAP5 Mod1 and Mod2, MELCOR and ICARE2 and described the bundle degradation up to the final freezing of relocated materials. The second, including ATHLET SA, KESS III, FRAS-SFD and MARCH3 were limited to the calculation of thermal behaviour and to the first oxidation process of rod degradation.

All the calculations performed with the first approach using a recommended measured ZrO₂ porous conductivity value led to an overestimation of rod temperatures. Correct thermal and oxidation behaviours of the rods were only calculated when the thermal leakage through the shroud was increased and adjusted.
The capabilities of the advanced codes for calculating the main degradation phenomena when the thermal-hydraulic conditions are known were clearly illustrated. Areas with inadequate understanding and modelling weaknesses were identified. The most severe limitations concerned simultaneous $\text{UO}_2$ - $\text{ZrO}_2$ dissolution by molten Zry for which $\text{ZrO}_2$ dissolution was not modelled except in one code, $\text{UO}_2$ solubility limits in the resulting $\text{U-Zr-O}$ mixture and cladding failure conditions by this molten mixture. There is also a general tendency to overestimate the relocation distance of these liquified mixtures. Finally, lacks were identified in the modelling of the Inconel spacer-grid interaction with both the rods and the relocated mixtures.

This first ISP on core degradation points out that more verification and validation work remains necessary for severe fuel damage computer codes which seem to be lagging behind current knowledge gained through experimental data on the early phase of core degradation.

The verification of reactor codes on small scale experiments needs more code versatility: power profile evolutions, surrounding structures with imposed boundary conditions, a pure non-condensable flow, more output convenience.

Finally this exercise also illustrates the importance of the code user, the need for improved user-guidelines with more detailed information and recommendations, as well as the need for experts in core degradation in order to make code utilization more effective with valuable jugements on predictions especially in these areas where code modelling deficiencies have been identified.
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ANNEX 1

FRA-SP CEA-PHEBUS SPANISH SUBMISSION
Figure 1
UO2 temperature of the second ring rod versus time at levels 20, 30, 40 and 50 cm

Figure 2
UO2 temperature of the second ring rod versus time at levels 60 and 70 cm
Final time: 18005 s

Cladding temperature of the first ring rod versus time at levels 20, 30, 40 and 50 cm

Figure 3

FRANCE
SPANISH Gnr
ICARE2 v2

Final time: 18005 s

Cladding temperature of the first ring rod versus time at levels 60 and 70 cm

Figure 4

FRANCE
SPANISH Gnr
ICARE2 v2
Final time: 18005 s

Fluid temperature of the mean channel versus time at levels 0, 30 and 40 cm

Figure 5

Final time: 18005 s

Fluid temperature of the mean channel versus time at levels 50 and 80 cm

Figure 6
Final time: 18005 s

Figure 7
Liner temperature versus time
at levels 40, 60 and 80 cm

Figure 8
Shroud temperature versus time
at levels 30, 40, 60 and 70 cm
Final time: 18005 s

Temperatures versus time at level 50 cm

Final time: 18005 s

Temperatures versus time at level 70 cm
Figure 11

Axial profiles: 7700, 9000, 12000, and 14000 s
Second ring rod UO2 temperature

Figure 12

Heat flux to the shroud versus time
at levels 20, 40, and 60 cm
Figure 25

OXIDATION PROFILE : 9000 s
Calculation: central rod and second ring rod

Figure 26

Δt02 LAYER INCREASE AND DISSOLUTION
First ring rod
Final time: 18005 s

ZrO2 MASS FRACTION VERSUS LEVEL
Zr LINER

Total H2 production - H2 mass flow rate
Computed and measured
**MEAN UO2 DISSOLUTION PROFILE : 18000 s**

Final time : 18005 s

**FLOW BLOCKAGE (Init : FB = 38%)**

Final time : 18005 s
Figure 31
TOTAL MASS OF RELOCATED MIXTURE

Figure 32
PICTURE OF THE BUNDLE
ANNEX 2

SP-CSN SUBMISSION
Final time : 17990 s

Figure 1
UO₂ temperature of the second ring rod versus time at levels 20, 30, 40 and 50 cm

Figure 2
UO₂ temperature of the second ring rod versus time at levels 60 and 70 cm
Cladding temperature of the first ring rod versus time at levels 20, 30, 40 and 50 cm

Figure 3

Cladding temperature of the first ring rod versus time at levels 60 and 70 cm

Figure 4
Final time : 17990 s

Fluid temperature of the mean channel versus time
at levels 0, 30 and 40 cm

---

Final time : 17990 s

Fluid temperature of the mean channel versus time
at levels 50 and 80 cm
Figure 7
Liner temperature versus time
at levels 40, 60 and 80 cm

Figure 8
Shroud temperature versus time
at levels 30, 40, 60 and 70 cm
Final time: 17990 s

Temperatures versus time at level 50 cm

Figure 9

Final time: 17990 s

Temperatures versus time at level 70 cm

Figure 10
Axial profiles: 7700, 9000, 12000 and 14000 s
Second ring rod U02 temperature

Heat flux to the shroud versus time
at levels 20, 40 and 60 cm
Figure 25

OXIDATION PROFILE: 9000 s
Calculation: central rod and second ring rod

Figure 26

ZrO2 LAYER INCREASE AND DISSOLUTION
First ring rod

Time (s)

0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5 10.0

LEVEL (m)

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8

(x)

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

Final time: 17990 s

SPAIN
CSN
SCDAP/MOD1
V20

1 0XCRZZ
2 0XRZLZ
Data 1R
Data 2R

1 20 cm
2 30 cm
3 40 cm
4 50 cm
5 60 cm
6 70 cm
7 75 cm

Final time: 17990 s
Final time: 17990 s

Zr02 MASS FRACTION VERSUS LEVEL
Zr LINER

Final time: 17990 s
TOTAL MASS H2 (G)

Total H2 production - H2 mass flow rate
Computed and measured
Final time: 17990 s

MEAN U02 DISSOLUTION PROFILE: 18000 s

FLOW BLOCKAGE (Init: FB = 38%)

Figure 29

Figure 30
Incorrect values on the transmittal file
TOTAL MASS OF UO₂ - ZrO₂ - Zr : 9000 s

TOTAL MASS OF UO₂ - ZrO₂ - Zr : 18000 s
ANNEX 3

SP-UPM SUBMISSION
Final time: 18000 s

Figure 1

UO2 temperature of the second ring rod versus time at levels 20, 30, 40 and 50 cm

Figure 2

UO2 temperature of the second ring rod versus time at levels 60 and 70 cm
Figure 3
Cladding temperature of the first ring rod versus time at levels 20, 30, 40 and 50 cm

Figure 4
Cladding temperature of the first ring rod versus time at levels 60 and 70 cm
Final time: 18000 s

Fluid temperature of the mean channel versus time at levels 0, 30 and 40 cm

Figure 5

SPAIN
CTN-UPM
MELCOR v1.80

Final time: 18000 s

Fluid temperature of the mean channel versus time at levels 50 and 80 cm

Figure 6

SPAIN
CTN-UPM
MELCOR v1.80
Figure 7
Liner temperature versus time
at levels 40, 60 and 80 cm

Figure 8
Shroud temperature versus time
at levels 30, 40, 60 and 70 cm
Figure 9
Temperatures versus time at level 50 cm

Figure 10
Temperatures versus time at level 70 cm
Final time: 18000 s

Axial profiles: 7700, 9000, 12000 and 14000 s
Second ring rod UO2 temperature

Heat flux to the shroud versus time at levels 20, 40 and 60 cm
**Figure 25**

**Final time : 18000 s**

**OXIDATION PROFILE : 9000 s**
Calculation: central rod and second ring rod

---

**Figure 26**

**Final time : 18000 s**

**Δρ02 LAYER INCREASE AND DISSOLUTION**
First ring rod
Final time: 18000 s

ZrO2 MASS FRACTION VERSUS LEVEL
Zr LINER

LINER NOT TAKEN INTO ACCOUNT FOR OXIDATION

Final time: 18000 s

TOTAL MASS H2 (G) MASS FLOW (MG/S)

Total H2 production - H2 mass flow rate
Computed and measured
Final time: 18000 s

Figure 29

MEAN UO2 DISSOLUTION PROFILE: 18000 s

SPAIN
CTN-UPM
FLCON V1.8.6

Final time: 18000 s

Figure 30

FLOW BLOCKAGE (Init: FB = 38%)

SPAIN
CTN-UPM
FLCON V1.8.6
Final time: 18000 s

TOTAL MASS OF RELOCATED MIXTURE

Figure 31

SPAIN
CTN-UPM
MELCOR V1.8.0
Figure 33
TOTAL MASS OF UO2 - ZrO2 - Zr : 9000 s

Figure 34
TOTAL MASS OF UO2 - ZrO2 - Zr : 18000 s
ANNEX 4

CZECHOSLOVAKIA-NRI SUBMISSION
UO2 temperature of the second ring rod versus time at levels 20, 30, 40 and 50 cm

Figure 1

UO2 temperature of the second ring rod versus time at levels 60 and 70 cm

Figure 2
Figure 3

Cladding temperature of the first ring rod versus time at levels 20, 30, 40 and 50 cm

Figure 4

Cladding temperature of the first ring rod versus time at levels 60 and 70 cm
Fluid temperature of the mean channel versus time at levels 0, 30 and 40 cm

Figure 5

Fluid temperature of the mean channel versus time at levels 50 and 80 cm

Figure 6
Figure 7

Liner temperature versus time
at levels 40, 60 and 80 cm

Figure 8

Shroud temperature versus time
at levels 30, 40, 60 and 70 cm
Temperatures versus time at level 50 cm

Temperatures versus time at level 70 cm
Axial profiles : 7700, 9000, 12000 and 14000 s
Second ring rod U02 temperature

Heat flux to the shroud versus time
at levels 20, 40 and 60 cm
OXIDATION PROFILE: 9000 s
Calculation: central rod and second ring rod

Figure 25

ZrO2 LAYER INCREASE AND DISSOLUTION
First ring rod

Figure 26
ZrO2 MASS FRACTION VERSUS LEVEL
Zr LINER

Final time: 8320 s

Figure 27

CZECH-BLLOWAH
NR REZ
FRAS-SFD

Final time: 8320 s

TOTAL MASS H2 (G) vs Mass Flow (MG/S)

Figure 28

CZECH-BLLOWAH
NR REZ
FRAS-SFD

Total H2 production — H2 mass flow rate
Computed and measured
Final time: 8320 s

MEAN UO2 DISSOLUTION PROFILE: 18000 s

FLOW BLOCKAGE (Init: FB = 38%)
ANNEX 5a

GER-IKE 1 SUBMISSION
(1st way BC)
Final time : 17900 s

UO₂ temperature of the second ring rod versus time at levels 20, 30, 40 and 50 cm

Final time : 17900 s

UO₂ temperature of the second ring rod versus time at levels 60 and 70 cm
Final time : 17900 s

Figure 3

Cladding temperature of the first ring rod versus time at levels 20, 30, 40 and 50 cm

Final time : 17900 s

Figure 4

Cladding temperature of the first ring rod versus time at levels 50 and 70 cm
Fluid temperature of the mean channel versus time
at levels 0, 30 and 40 cm

Final time : 17900 s

Fluid temperature of the mean channel versus time
at levels 50 and 80 cm

Final time : 17900 s
Final time : 17900 s

Figure 7

Liner temperature versus time
at levels 40, 60 and 80 cm

Final time : 17900 s

Figure 8

Shroud temperature versus time
at levels 30, 40, 60 and 70 cm
Final time: 17900 s

Temperatures versus time at level 50 cm

Final time: 17900 s

Temperatures versus time at level 70 cm
Final time: 17900 s

Figure 11
Axial profiles: 7700, 9000, 12000 and 14000 s
Second ring rod U02 temperature

Final time: 17900 s

Figure 12
Heat flux to the shroud versus time
at levels 20, 40 and 60 cm
Final time: 17900 s

Oxidation Profile: 9000 s
Calculation: central rod and second ring rod

Final time: 17900 s

Δ02 Layer Increase and Dissolution
First ring rod
ZrO2 MASS FRACTION VERSUS LEVEL
Zr LINER

Final time: 17900 s

Total H2 production – H2 mass flow rate
Computed and measured
MEAN UO2 DISSOLUTION PROFILE : 18000 s

FLOW BLOCKAGE (Init : FB = 38%)
ANNEX 5b

GER-IKE2 SUBMISSION
(2nd way BC)
UO₂ temperature of the second ring rod versus time at levels 20, 30, 40 and 50 cm

Final time : 18000 s

Figure 1

UO₂ temperature of the second ring rod versus time at levels 60 and 70 cm

Final time : 18000 s

Figure 2
Final time: 18000 s

Cladding temperature of the first ring rod versus time at levels 20, 30, 40 and 50 cm

Figure 3

Final time: 18000 s

Cladding temperature of the first ring rod versus time at levels 60 and 70 cm

Figure 4
Final time : 18000 s

Fluid temperature of the mean channel versus time at levels 0, 30 and 40 cm

---

Final time : 18000 s

Fluid temperature of the mean channel versus time at levels 50 and 80 cm
Figure 7
Liner temperature versus time
at levels 40, 60 and 80 cm

Figure 8
Shroud temperature versus time
at levels 30, 40, 60 and 70 cm

GERMANY
KE 2
KSS-2 V1.1
Temperatures versus time at level 50 cm

Temperatures versus time at level 70 cm
**Figure 11**

Axial profiles: 7700, 9000, 12000 and 14000 s
Second ring rod UO2 temperature

**Figure 12**

Heat flux to the shroud versus time at levels 20, 40 and 50 cm
**Figure 25**

**OXIDATION PROFILE : 9000 s**
Calculation: central rod and second ring rod

**Final time : 18000 s**

**Figure 26**

**4:02 LAYER INCREASE AND DISSOLUTION**
First ring rod
Final time : 18000 s

ZrO2 MASS FRACTION VERSUS LEVEL
Zr LINER

Final time : 18000 s

Total H2 production - H2 mass flow rate
Computed and measured
Final time: 18000 s

Figure 29
MEAN UO2 DISSOLUTION PROFILE: 18000 s

Figure 30
FLOW BLOCKAGE (Init: FB = 38%)
ANNEX 6a

GER-GRS1 SUBMISSION
(1st way BC)
Figure 1
UO2 temperature of the second ring rod versus time at levels 20, 30, 40 and 50 cm

Figure 2
UO2 temperature of the second ring rod versus time at levels 60 and 70 cm
Figure 3
Cladding temperature of the first ring rod versus time at levels 20, 30, 40 and 50 cm

Figure 4
Cladding temperature of the first ring rod versus time at levels 60 and 70 cm
Fluid temperature of the mean channel versus time at levels 0, 30 and 40 cm

Final time: 17108 s

Figure 5

Fluid temperature of the mean channel versus time at levels 50 and 80 cm

Final time: 17108 s

Figure 6
Figure 7
Liner temperature versus time
at levels 40, 60 and 80 cm

Final time: 17108 s

Figure 8
Shroud temperature versus time
at levels 30, 40, 60 and 70 cm

Final time: 17108 s
Figure 9
Temperatures versus time at level 50 cm

Figure 10
Temperatures versus time at level 70 cm
Final time: 17108 s

Axial profiles: 7700, 9000, 12000 and 14000 s
Second ring rod U02 temperature

Final time: 17108 s

Heat flux to the shroud versus time
at levels 20, 40 and 60 cm
Oxidation Profile: 9000 s
Calculation: central rod and second ring rod

Final time: 17108 s

Layer Increase and Dissolution
First ring rod
Final time: 17108 s

Figure 29

MEAN UO2 DISSOLUTION PROFILE: 18000 s

Figure 30

FLOW BLOCKAGE (Init: FB = 38%)
ANNEX 6b

GER-GRS2 SUBMISSION
(2nd way BC)
Figure 1
UO2 temperature of the second ring rod versus time at levels 20, 30, 40 and 50 cm

Figure 2
UO2 temperature of the second ring rod versus time at levels 60 and 70 cm
Figure 3
Cladding temperature of the first ring rod versus time at levels 20, 30, 40 and 50 cm

Figure 4
Cladding temperature of the first ring rod versus time at levels 60 and 70 cm
Figure 5
Fluid temperature of the mean channel versus time at levels 0, 30 and 40 cm

Figure 6
Fluid temperature of the mean channel versus time at levels 50 and 80 cm
Figure 7
Liner temperature versus time
at levels 40, 60 and 80 cm

Figure 8
Shroud temperature versus time
at levels 30, 40, 60 and 70 cm
Figure 9
Temperatures versus time at level 50 cm

Final time : 17967 s

Figure 10
Temperatures versus time at level 70 cm

Final time : 17967 s
Final time: 17967 s

Figure 11
Axial profiles: 7700, 9000, 12000 and 14000 s
Second ring rod UO2 temperature

Final time: 17967 s

Figure 12
Heat flux to the shroud versus time
at levels 20, 40 and 60 cm
OXIDATION PROFILE : 9000 s
Calculation : central rod and second ring rod

Zr02 LAYER INCREASE AND DISSOLUTION
First ring rod

Final time : 17967 s
Final time: 17967 s

ZrO2 MASS FRACTION VERSUS LEVEL
Zr LINER

Total H2 production - H2 mass flow rate
Computed and measured
ANNEX 7

HUNGARY-CRIP SUBMISSION
Final time : 8382 s

UO2 temperature of the second ring rod versus time at levels 20, 30, 40 and 50 cm

Figure 1

Final time : 8382 s

UO2 temperature of the second ring rod versus time at levels 60 and 70 cm

Figure 2
Final time: 8382 s

Figure 3

Cladding temperature of the first ring rod versus time at levels 20, 30, 40 and 50 cm

Figure 4

Cladding temperature of the first ring rod versus time at levels 60 and 70 cm
Figure 5
Fluid temperature of the mean channel versus time at levels 0, 30 and 40 cm

Figure 6
Fluid temperature of the mean channel versus time at levels 50 and 80 cm
Final time: 8382 s

Figure 7

Liner temperature versus time
at levels 40, 60 and 80 cm

Figure 8

Shroud temperature versus time
at levels 30, 40, 60 and 70 cm
Temperatures versus time at level 50 cm

Final time: 8382 s

Temperatures versus time at level 70 cm

Final time: 8382 s
Final time: 8382 s

Axial profiles: 7700, 9000, 12000 and 14000 s
Second ring rod UO2 temperature

Final time: 8382 s

Heat flux to the shroud versus time at levels 20, 40 and 60 cm
OXIDATION PROFILE: 9000 s
Calculation: central rod and second ring rod

_LAYER INCREASE AND DISSOLUTION_
First ring rod
ZrO2 MASS FRACTION VERSUS LEVEL
Zr LINER

Final time: 8382 s

Figure 27

HUNGARY
C.R.I.P.
MARCH3

Mass Computed and measured

Total H2 production - H2 mass flow rate

Figure 28

HUNGARY
C.R.I.P.
MARCH3
Final time: 8382 s

MEAN UO2 DISSOLUTION PROFILE: 18000 s

FLOW BLOCKAGE (Init: FB = 38%)
Final time: 18000 s

UO2 temperature of the second ring rod versus time at levels 20, 30, 40 and 50 cm

Figure 1

Final time: 18000 s

UO2 temperature of the second ring rod versus time at levels 60 and 70 cm

Figure 2
Figure 3

Cladding temperature of the first ring rod versus time at levels 20, 30, 40 and 50 cm

Figure 4

Cladding temperature of the first ring rod versus time at levels 50 and 70 cm
Figure 5

Fluid temperature of the mean channel versus time at levels 0, 30 and 40 cm

Figure 6

Fluid temperature of the mean channel versus time at levels 50 and 80 cm
Final time : 18000 s

Figure 7
ITALY
Univ. of Pisa
SCDAP/RELAP5
MOD2

Liner temperature versus time
at levels 40, 60 and 80 cm

Final time : 18000 s

Figure 8
ITALY
Univ. of Pisa
SCDAP/RELAP5
MOD2

Shroud temperature versus time
at levels 30, 40, 60 and 70 cm
Figure 9
Temperatures versus time at level 50 cm

Figure 10
Temperatures versus time at level 70 cm
Final time: 18000 s

Axial profiles: 7700, 9000, 12000 and 14000 s
Second ring rod UO2 temperature

Figure 11

Final time: 18000 s

Heat flux to the shroud versus time at levels 20, 40 and 60 cm

Figure 12
Final time: 18000 s

OXIDATION PROFILE: 9000 s
Calculation: central rod and second ring rod

Final time: 18000 s

Δl02 LAYER INCREASE AND DISSOLUTION
First ring rod
Figure 27
ZrO2 MASS FRACTION VERSUS LEVEL
Zr LINER

Figure 28
Total H2 production - H2 mass flow rate
Computed and measured
Final time: 18000 s

MEAN UO2 DISSOLUTION PROFILE: 18000 s

FLOW BLOCKAGE (Init: FB = 38%)
Final time: 18000 s

Figure 31

TOTAL MASS OF RELOCATED MIXTURE

ITALY

UWI of Pisa
BCCAP/RELAPS
MOD02
PICTURE OF THE BUNDLE

- Central fuel rod configuration at 18000 s.
- First ring fuel configuration at 18000 s.
- Second ring fuel rod configuration at 18000 s.

Figure 32  ITALY

Univ. of PISA
ANNEX 9

ISPRA SUBMISSION
Final time: 17993 s

UO2 temperature of the second ring rod versus time at levels 20, 30, 40 and 50 cm

Figure 1

C.E.C.
ISPRA
KARE2 v1

Final time: 17993 s

UO2 temperature of the second ring rod versus time at levels 50 and 70 cm

Figure 2

C.E.C.
ISPRA
KARE2 v1
Figure 3
Cladding temperature of the first ring rod versus time at levels 20, 30, 40 and 50 cm

Figure 4
Cladding temperature of the first ring rod versus time at levels 60 and 70 cm
Final time: 17993 s

Fluid temperature of the mean channel versus time at levels 0, 30 and 40 cm

Figure 5

Fluid temperature of the mean channel versus time at levels 50 and 80 cm

Figure 6
Figure 7
Liner temperature versus time
at levels 40, 60 and 80 cm

Figure 8
Shroud temperature versus time
at levels 30, 40, 60 and 70 cm
Temperatures versus time at level 50 cm

Final time: 17993 s

Temperatures versus time at level 70 cm

Final time: 17993 s
Final time: 17993 s

Axial profiles: 7700, 9000, 12000 and 14000 s
Second ring rod UO2 temperature

Heat flux to the shroud versus time
at levels 20, 40 and 60 cm
Figure 25

OXIDATION PROFILE : 9000 s
Calculation : central rod and second ring rod

Figure 26

402 LAYER INCREASE AND DISSOLUTION
First ring rod
Figure 27
ZrO2 MASS FRACTION VERSUS LEVEL
Zr LINER

Figure 28
Total H2 production - H2 mass flow rate
Computed and measured

C.E.C.
J.R.C.
ICARE2 v1
MEAN UO2 DISSOLUTION PROFILE : 18000 s

FLOW BLOCKAGE (Init : FB = 38%)
Figure 32 non transmitted
Final time: 17990 s

UO2 temperature of the second ring rod versus time at levels 20, 30, 40 and 50 cm

Final time: 17990 s

UO2 temperature of the second ring rod versus time at levels 50 and 70 cm
Cladding temperature of the first ring rod versus time at levels 20, 30, 40 and 50 cm

Figure 3

Cladding temperature of the first ring rod versus time at levels 60 and 70 cm

Figure 4
Fluid temperature of the mean channel versus time at levels 0, 30 and 40 cm

Figure 5

Fluid temperature of the mean channel versus time at levels 50 and 80 cm

Figure 6
Figure 7
Liner temperature versus time
at levels 40, 60 and 80 cm

Final time: 17990 s

Figure 8
Shroud temperature versus time
at levels 30, 40, 60 and 70 cm

Final time: 17990 s
Final time: 17990 s

Temperatures versus time at level 50 cm

Final time: 17990 s

Temperatures versus time at level 70 cm
Final time: 17990 s

Axial profiles: 7700, 9000, 12000 and 14000 s
Second ring rod UO2 temperature

Final time: 17990 s

Missing parameter on the transmittal file

Heat flux to the shroud versus time
at levels 20, 40 and 60 cm
Final time: 17990 s

**Figure 25**

**OXIDATION PROFILE: 9000 s**
Calculation: central rod and second ring rod

**Figure 26**

**Z102 LAYER INCREASE AND DISSOLUTION**
First ring rod
Final time: 17990 s

ZrO2 MASS FRACTION VERSUS LEVEL
Zr LINER

Final time: 17990 s

TOTAL MASS H2 (G) vs MASS FLOW (MG/S)

Total H2 production - H2 mass flow rate
Computed and measured
Mean UO2 Dissolution Profile: 18000 s

Flow Blockage (Init: FB = 38%)
ANNEX 11

NETHERLANDS-ECN SUBMISSION
Final time: 13990 s

Figure 1
UO2 temperature of the second ring rod versus time at levels 20, 30, 40 and 50 cm

Figure 2
UO2 temperature of the second ring rod versus time at levels 60 and 70 cm
Cladding temperature of the first ring rod versus time
at levels 20, 30, 40 and 50 cm

Final time : 13990 s

Figure 3

Cladding temperature of the first ring rod versus time
at levels 60 and 70 cm

Final time : 13990 s

Figure 4
Figure 5
Fluid temperature of the mean channel versus time at levels 0, 30 and 40 cm

Figure 6
Fluid temperature of the mean channel versus time at levels 50 and 80 cm
Final time: 13990 s

Liner temperature versus time
at levels 40, 60 and 80 cm

Figure 7

Shroud temperature versus time
at levels 30, 40, 60 and 70 cm

Figure 8
Axial profiles: 7700, 9000, 12000 and 14000 s
Second ring rod UO2 temperature

Heat flux to the shroud versus time
at levels 20, 40 and 60 cm
OXIDATION PROFILE: 9000 s
Calculation: central rod and second ring rod

Final time: 13990 s

Figure 25

Figure 26

△02 LAYER INCREASE AND DISSOLUTION
First ring rod
Figure 29
MEAN UO2 DISSOLUTION PROFILE: 18000 s

Figure 30
FLOW BLOCKAGE (Init: FB = 38%)
Figure 33
TOTAL MASS OF UO2 – ZrO2 – Zr : 9000 s

Figure 34
TOTAL MASS OF UO2 – ZrO2 – Zr : 18000 s
ANNEX 12

SWEDEN-SN SUBMISSION
Figure 1
UO2 temperature of the second ring rod versus time at levels 20, 30, 40 and 50 cm

Figure 2
UO2 temperature of the second ring rod versus time at levels 60 and 70 cm
Cladding temperature of the first ring rod versus time at levels 20, 30, 40 and 50 cm

Cladding temperature of the first ring rod versus time at levels 60 and 70 cm
Final time: 18000 s

Figure 5
Fluid temperature of the mean channel versus time at levels 0, 30 and 40 cm.

Figure 6
Fluid temperature of the mean channel versus time at levels 50 and 80 cm.
Liner temperature versus time
at levels 40, 60 and 80 cm

Shroud temperature versus time
at levels 30, 40, 60 and 70 cm
Final time: 18000 s

Temperatures versus time at level 50 cm

Final time: 18000 s

Temperatures versus time at level 70 cm
Final time: 18000 s

Axial profiles: 7700, 9000, 12000 and 14000 s
Second ring rod UO2 temperature

Final time: 18000 s

Heat flux to the shroud versus time
at levels 20, 40 and 60 cm
Figure 25

OXIDATION PROFILE: 9000 s
Calculation: central rod and second ring rod

Figure 26

Δt\text{02 LAYER INCREASE AND DISSOLUTION}
First ring rod
ZrO2 MASS FRACTION VERSUS LEVEL
Zr LINER

Final time : 18000 s

Total H2 production - H2 mass flow rate
Computed and measured

Figure 27

Figure 28
Final time: 18000 s

**Figure 29**

MEAN UO2 DISSOLUTION PROFILE: 18000 s

Final time: 18000 s

**Figure 30**

FLOW BLOCKAGE (Init: FB = 38%)
Figure 33
TOTAL MASS OF UO₂ - ZrO₂ - Zr : 9000 s

Figure 34
TOTAL MASS OF UO₂ - ZrO₂ - Zr : 18000 s
Final time: 17960 s

**Figure 1**

UO2 temperature of the second ring rod versus time at levels 20, 30, 40 and 50 cm

**Figure 2**

UO2 temperature of the second ring rod versus time at levels 60 and 70 cm
Figure 3
Cladding temperature of the first ring rod versus time at levels 20, 30, 40 and 50 cm

Figure 4
Cladding temperature of the first ring rod versus time at levels 60 and 70 cm
Final time : 17960 s

Fluid temperature of the mean channel versus time at levels 0, 30 and 40 cm

Figure 5

Fluid temperature of the mean channel versus time at levels 50 and 80 cm

Figure 6
Final time: 17960 s

Liner temperature versus time at levels 40, 60 and 80 cm

Shroud temperature versus time at levels 30, 40, 60 and 70 cm
Final time: 17960 s

Temperatures versus time at level 50 cm

Figure 9

Temperatures versus time at level 70 cm

Figure 10
Final time: 17960 s

Axial profiles: 7700, 9000, 12000 and 14000 s
Second ring rod UO2 temperature

Heat flux to the shroud versus time
at levels 20, 40 and 60 cm
Final time: 17960 s

OXIDATION PROFILE: 9000 s
Calculation: central rod and second ring rod

ZrO2 LAYER INCREASE AND DISSOLUTION
First ring rod
ZrO2 MASS FRACTION VERSUS LEVEL
Zr LINER

Figure 27
TAWAN
A.E.C.
MELCOR V1.80

Final time: 17960 s

Figure 28
TAWAN
A.E.C.
MELCOR V1.80

Total H2 production – H2 mass flow rate
Computed and measured
Final time: 17960 s

TOTAL MASS OF RELOCATED MIXTURE

Figure 32 non transmitted
ANNEX 14

UK-AEA TECHNOLOGY SUBMISSION
Figure 1

UO2 temperature of the second ring rod versus time at levels 20, 30, 40 and 50 cm

Figure 2

UO2 temperature of the second ring rod versus time at levels 60 and 70 cm
Final time: 18000 s

Cladding temperature of the first ring rod versus time at levels 20, 30, 40 and 50 cm

Figure 3

Final time: 18000 s

Cladding temperature of the first ring rod versus time at levels 60 and 70 cm

Figure 4
Figure 5

Fluid temperature of the mean channel versus time at levels 0, 30 and 40 cm

Figure 6

Fluid temperature of the mean channel versus time at levels 50 and 80 cm
Final time: 18000 s

Liner temperature versus time
at levels 40, 60 and 80 cm

Figure 7
U.K.
AEA WRAPRTH
SELAP 3618c

Final time: 18000 s

Shroud temperature versus time
at levels 30, 40, 60 and 70 cm

Figure 8
U.K.
AEA WRAPRTH
SELAP 3618c
Final time: 18000 s

Temperatures versus time at level 50 cm

Final time: 18000 s

Temperatures versus time at level 70 cm
Final time: 18000 s

Axial profiles: 7700, 9000, 12000 and 14000 s
Second ring rod UO2 temperature

Final time: 18000 s

Heat flux to the shroud versus time
at levels 20, 40 and 60 cm
Final time: 18000 s

Figure 25

OXIDATION PROFILE: 9000 s
Calculation: central rod and second ring rod

Final time: 18000 s

Figure 26

1.70 cm
2.30 cm
3.40 cm
4.50 cm
5.60 cm
6.70 cm
7.75 cm

1.0 cm LAYER INCREASE AND DISSOLUTION
central rod
ZrO2 MASS FRACTION VERSUS LEVEL

Zr LINER

Final time: 18000 s

Figure 27

U.K.
AEA WINTH
SOLAP 361bc

Total H2 production - H2 mass flow rate
Computed and measured

Figure 28

U.K.
AEA WINTH
SOLAP 361bc
MEAN UO2 DISSOLUTION PROFILE : 18000 s

FLOW BLOCKAGE (init : FB = 38%)
Missing parameter on the transmittal file

TOTAL MASS OF UO2 – ZrO2 – Zr : 9000 s

TOTAL MASS OF UO2 – ZrO2 – Zr : 18000 s
ANNEX 15

USA-NRC SUBMISSION
Final time: 17960 s

UO2 temperature of the second ring rod versus time at levels 20, 30, 40 and 50 cm

Figure 1

U.S.A.
NRC. SNL
MELCOR V1.2A

Final time: 17960 s

UO2 temperature of the second ring rod versus time at levels 50 and 70 cm

Figure 2

U.S.A.
NRC. SNL
MELCOR V1.2A
Final time: 17960 s

Cladding temperature of the first ring rod versus time at levels 20, 30, 40 and 50 cm

Final time: 17960 s

Cladding temperature of the first ring rod versus time at levels 60 and 70 cm
Figure 5
Fluid temperature of the mean channel versus time at levels 0, 30 and 40 cm

Figure 6
Fluid temperature of the mean channel versus time at levels 50 and 80 cm
Figure 7
Liner temperature versus time
at levels 40, 60 and 80 cm

Figure 8
Shroud temperature versus time
at levels 30, 40, 60 and 70 cm
Final time: 17960 s

Temperatures versus time at level 50 cm

Final time: 17960 s

Temperatures versus time at level 70 cm
Axial profiles: 7700, 9000, 12000 and 14000 s
Second ring rod UO2 temperature

Final time: 17960 s

Heat flux to the shroud versus time
at levels 20, 40 and 60 cm
Final time : 17960 s

Figure 25

OXIDATION PROFILE : 9000 s
Calculation : central rod and second ring rod

Final time : 17960 s

Figure 26

\( \alpha_0^2 \) LAYER INCREASE AND DISSOLUTION
First ring rod
ZrO₂ MASS FRACTION VERSUS LEVEL
Zr LINER

Final time: 17960 s

Figure 27

Total H₂ production - H₂ mass flow rate
Computed and measured

Figure 28
Final time: 17960 s

MEAN UO2 DISSOLUTION PROFILE: 18000 s

FLOW BLOCKAGE (Init: FB = 38%)
Schematic Picture of the State and Material Composition of the Fuel Bundle at 18000 seconds.
ANNEX 16

COMPARISONS BETWEEN CODES
TU2R30 : UO2 TEMPERATURE - 2nd RING ROD
LEVEL 30 cm

TU2R50 : UO2 TEMPERATURE - 2nd RING ROD
LEVEL 50 cm
TU2R60: UO2 TEMPERATURE - 2nd RING ROD
LEVEL 60 cm

TU2R70: UO2 TEMPERATURE - 2nd RING ROD
LEVEL 70 cm
TU2R60 : UO2 TEMPERATURE – 2nd RING ROD LEVEL 60 cm

TU2R70 : UO2 TEMPERATURE – 2nd RING ROD LEVEL 70 cm
TSR160 : LINER TEMPERATURE
LEVEL 60 cm

Fig 5/1

TSR360 : SHROUD TEMPERATURE
LEVEL 60 cm

Fig 6/1
TSR160 : LINER TEMPERATURE
LEVEL 60 cm

TSR360 : SHROUD TEMPERATURE
LEVEL 60 cm
OX1RZZ : 1st RING ROD OXIDATION VERSUS TIME
LEVEL 40 cm

OX1RZZ : 1st RING ROD OXIDATION VERSUS TIME
LEVEL 50 cm
OX1RZZ : 1st RING ROD OXIDATION VERSUS TIME
LEVEL 40 cm

OX1RZZ : 1st RING ROD OXIDATION VERSUS TIME
LEVEL 50 cm
OX1RZZ : 1st RING ROD OXIDATION VERSUS TIME
LEVEL 40 cm

OX1RZZ : 1st RING ROD OXIDATION VERSUS TIME
LEVEL 50 cm
OX1RZZ : 1st RING ROD OXIDATION VERSUS TIME
LEVEL 60 cm

OX1RZZ : 1st RING ROD OXIDATION VERSUS TIME
LEVEL 70 cm
OX1RZZ : 1st RING ROD OXIDATION VERSUS TIME
LEVEL 60 cm

OX1RZZ : 1st RING ROD OXIDATION VERSUS TIME
LEVEL 70 cm
OX1RZZ : 1st RING ROD OXIDATION VERSUS TIME
LEVEL 60 cm

Fig 9/3

OX1RZZ : 1st RING ROD OXIDATION VERSUS TIME
LEVEL 70 cm

Fig 10/3
HYDROTOT : TOTAL H2 RELEASE

OX1RZZ : 1st RING ROD OXIDATION VERSUS ELEVATION at 9000 s
HYDTOT : TOTAL H2 RELEASE

OX1RZZ : 1st RING ROD OXIDATION VERSUS ELEVATION at 9000 s

Fig 11/2

Fig 12/2
HYDTOT : TOTAL H2 RELEASE

Fig 11/3

OXIRZZ : 1st RING ROD OXIDATION VERSUS ELEVATION at 9000 s

Fig 12/3
DUMEAN UO2 DISSOLUTION VERSUS ELEVATION
AT 14000 s

COBKZZ : CORE BLOCKAGE — (INITIAL VALUE = 38%)
at 14000 s
DUMEN: U02 DISSOLUTION VERSUS ELEVATION
AT 14000 s

CUBK/LZ: CORE BLOCKAGE - (INITIAL VALUE = 38%)
at 14000 s
DUMEAU UO2 DISSOLUTION VERSUS ELEVATION
AT 14000 s

COBZ02 : CORE BLOCKAGE = (INITIAL VALUE = 38%)
at 14000 s
--- Failures zones by molten Zr
1: CR rods  2: 1R rods  3: 2R rods  L liner  +++ Debris bed

Frozen mixtures  Mixture with Inconel

Fig. 15
ANNEX 17

PLOT IDENTIFIERS
### PLOT IDENTIFIERS

Plot Identifiers (PI) are the name of the different parameters to be calculated and plotted.

Each identifier will count six letters; the two first one indicate the kind of parameter, the two following ones characterize the structure location or the fluid and the two last ones the axial level in the bundle.

| Names of the plot identifiers (PI) | \(XX|YY|WW\) |
|-----------------------------------|-------------|
| **MEANING OF XX**  |  |
| TF | fluid temperature |
| TU | \(\text{UO}_2\) temperature |
| TC | cladding temperature |
| TS | shroud temperature |
| OX | oxidation layer |
| DU | \(\text{UO}_2\) dissolution |
| DZ | \(\text{ZrO}_2\) dissolution |
| TM | total mass |
| HF | heat flux |
| **MEANING OF YY**  |  |
| CH | mean fluid channel |
| CR | central rod |
| 1R | first ring rod |
| 2R | 2nd ring rod |
| R1 | internal zircaloy liner |
| R2 | external zircaloy liner |
| R3 | porous zirconia (location at one third thickness from the external side) |
| UO | \(\text{UO}_2\) |
| ZO | \(\text{ZrO}_2\) |
| ZR | zircaloy |
MEANING OF WW : the 10 axial instrumented locations :
00 - 05 - 20 - 30 - 40 - 50 - 60 - 70 - 75 - 80

Escaping to this rule, it remains the following parameters :

COBKZZ which express the COre BlocKage table.
TIME^^ which express the TIME
TISTEP which express the TIme STEP in the calculation
HFRATE which express the Hydrogen mass Flow RATE
HYDTOT TOTal HYDrogen production
TMUZRO TOTal mass of U - ZR - O mixture

Remarks : - All the PI names have 6 characters and can contain blanks (^).
- When the 2 last letters of a PI name are ZZ, the PI is a table with 10
differsnts values which correspond to the 10 different elevations from 00
to 80 cm. This rule does not apply to the table ZLEVEL.