Pre-Test Analysis of QUENCH-20 BWR-Bundle with ASTEC

ASTEC-Team at KIT
Presenter: S. Wang
Content

- Motivation
- Quench-20 experiment
- ASTEC Modeling & Input
- Calculation Result & Analysis
- Summary
Motivation

• The new Version of ASTEC, It’s capabilities to simulate BWR-bundle tests;

• Pre-test Simulation Results to support experiment staffs;

• To review the ASTEC capabilities to simulate BWR Plants.
Quench-20 Experiment
The main component of the QUENCH facility is the test bundle.

Superheated steam + argon as a carrier gas enters the bundle at the bottom.

The argon, the not consumed steam, the generated hydrogen exit the bundle at the top.

The reflooding water enters the test section through a separate line at the bottom of the bundle.
Pre-test simulation of QUENCH-20 (SAFEST)

SSM proposal: study of high temperature degradation of BWR assembly mock-up in QUENCH facility (melt formation due to eutectical material interaction inside absorber cross)

Assembly SVEA-96 Optima

Absorber cross blade
QUENCH-20: suggested test bundle composition (¼ SVEA-96 OPTIMA2 assembly)

- **Absorber blades with B$_4$C, side length 83 mm**
- **Corner rod (Zry-4, OD 6 mm)**
- **Water channel box (ZIRLO), side length 27.4 mm**
- **Water cross wing (ZIRLO), wall thickness 0.8 mm**
- **Zr shroud 86 mm, wall thickness 3 mm**
- **ZrO$_2$ porous thermal insulation**
- **Advanced low tin ZIRLO fuel channel box, wall thickness 1.4 mm**

**Inconel cooling jacket, inner tube ID=158.3 mm**

**Geometrical parameters:**
- Bundle pitch 12.898 mm;
- Outer diameter of claddings 9.84 mm;
- Thickness of claddings 0.605 mm;
- Absorber blades: thickness 8.05 mm
- Cladding length 2500 mm
- Absorber and channel box lengths 1600 mm
Suggested scenario for QUENCH20-SAFEST

Liquefaction of B4C by solid SS

Expected Temp. Progress

stabilisation | heat-up | pre-oxidation | transient | quench

Time

Power Input

H2

Onset Zr Oxidation

Zr Oxidation increase

Water, 50 g/s (~400 s)

Ar, 3 g/s

Superheated steam (783 K), 3 g/s

corner rod

60 s before transient

1423 K

~3600 s → 150 μm ZrO2

~1200 s

18 kW

~4 kW

2000 K

~1.5 h

~1 h

~2500 s

~4 kW

~10 kW

11 kW

5400

9000

11500

15100

16300

17400

25th International QUENCH-Workshop, 22 - 24 October 2019, KIT
Core degradation modelling

Main phenomena to take into account

**T (K)**
- 3120: UO₂ melting
- 2960: ZrO₂ melting
- 2800: UO₂-ZrO₂ dissolution
- 2720: B₄C melting
- 2500

**LATE PHASE**
- Degraded

- 2030: Onset of Zr melting
- 1850: Zr oxidation increase
- 1730: Stainless steel melting
- 1670: Eutectic interactions
  - SIC - Zr
  - S.Steel - Zr
- 1500

**EARLY PHASE**
- Intact

- 1420: B₄C - S.Steel dissolution
- 1300: Onset of Zr oxidation
- 1200: Clad burst
- 1100: SIC control rod melting

**CORE COLLAPSE AND RELOCATION**

**MOLTEN POOL FORMATION**

**PARTIAL FUEL MELTING**
**CORE BLOCKAGES**
(Ceramic melts)

**FISSION PRODUCT RELEASES**

**H₂ Production Rate**

**CR Cladding melting**

**LOCAL**
**CORE DAMAGES**
(metallic melts)

**Liquefaction of B₄C by solid SS**

**H₂ Production**
ASTEC Modeling & Input
Quench-20 Cross Section and Heated Rod

3 Channels

3 Channels

z_{\text{max}}=1.5

z_{\text{maxB}}=1.3

z_{\text{maxW}}=1.024

(d_{\text{TUNG}}) \ 0/5

(d_{\text{PZO}}) \ 8.48/5.2

(d_{\text{CLAD}}) \ 8.63/9.84

z_{\text{minW}}=0

(d_{\text{MOCU}}) \ 0/7.85

z_{\text{CU}}=0.3

(d_{\text{IE}}) \ 7.85/8.25

z_{\text{min}}=0.475

ZrO2 coating
0.2 mm

Mo

W

CLAD(Zy-2)

PZO(ZrO2)

ELEC
Quench- 20 Bundle Axial Arrangement

$z_{\text{max}}=1.5$

$z_{\text{maxB}}=1.3$

$z_{\text{maxW}}=1.024$

$1600$

$z_{\text{minW}}=0$

$z_{\text{CU}}=-0.3$

$z_{\text{min}}=-0.475$

Flansch shroudrohr oben

Flansch shroudrohr unten

H$2O$ cooling jacket

Ar cooling jacket

Heated Length
HT: Radiative heat exchanges in a bundle

STRU RADB
[bundle]: geometric parameters
[bundle]: location parameters
[shroud]: diameter; **Obligatory**: cylinder
[radiative model]: parameters

Shroud type: cylinder
Oxidation of $\text{B}_4\text{C}$ module: Vessel: BCox

$\text{B}_4\text{C}$ – S. Steel dissolution module: Vessel: BCSS

MACRO WALL

It is not possible: cylinder in wall.
Oxidation B4C & liquefaction of B4C by solid SS (3/4)

\[ \text{WATBOX: } d = 77.5088 \quad \text{BZIR(Shroud): } 100.44 \]

\[ \text{CR\_ring: } d = (77.5088 + 100.44) / 2 = 88.9744 \]
\[ r_{ \text{CR\_ring} } = 44.4872 \]

\[ d = \sqrt{8.05 \times 8 / \pi} = 9.055 \]

\[ \text{pitch} = 09.055 \]

\[ \text{number} = \pi \times 44.4872 / \text{pitch} = 15.43 \]
Oxidation B4C & liquefaction of B4C by solid SS (4/4)

**WATBOX-Bundle-Shroud** radiation Heat exchange

**STRU RADB**
[bundle]: **WATBOX**: position & geometry
[bundle]: **CR cylinders**: positions & geom.
[shroud]: shroud; **Obligatory**: cylinder
[radiative model]: parameters
Total Power Input & Power distribution in bundles

Total Power (W)

- Power (W)
- transient
- quench
- Heat-up
- Pre-oxi
- stabili

Power in Channel (i) = Power * [(bundle_number_in_channel (i)] / [ total_number]
Thermal B.C.; BCTZ: Impose thermal conditions on a face of MACR at given elevations (1/2)

At given Macro Surface & Z-elevations:
e.g.: cooling jacket z=1.14
{H(i), time(i), external_Temperature(i)}

MACR 'BSS1' FACE 'EXTERNAL' TYPE 'BCTZ'
ZMIN ZMAX ! restrict domain
Z 1.14
SR1 H(i) ! [W/(m2.K)]
SR1 INST ! Instant (s)
SR1 TIMP ! External medium
! temperature (K)
Thermal B.C.; BCTZ: Impose thermal conditions on a face of MACR at given elevations (2/2)

Q8-Temp (K) at Z=1.14

Extrapolated Q20-Temp (K) Z=1.14
Calculation Results
Central Rod max. Temp. Development

1850K; Zr Oxi. increase

1300K; Zr Oxi. Beg.
Heated Centr- Rod Zr, ZrO & ZrO2 Thicknesses

- Zr_538 (mm)
- OZr_538(mm)
- O2Zr_538(mm)

150 µm ZrO₂

Heat-up
Pre-oxi
Transient
Quench

5400  9000  11500  15100  16300
H2 production rate & Accumulated H2 mass

1850K, H2 Production Rate

1300K: Onset of Zr Oxidation
Total Zr, ZrO & ZrO2 Mass Development
Cladding Temperature Profile at max Power Instant

Temperatures profile CLADs

- 1300K: Onset of Zr Oxidation
- 2030K: Onset of Zr Melting

Zr Oxidation Region

16301 33
Channel Box, CR-cladding & CR Temperature Profile

Zr Oxidation Region

Temperatures profile WATBOX Absorber

1730K: S.Steel melting

1300K: Zr-Zr eutectic interaction

1500-1670K: S.Steel-Zr eutectic interaction
S. Steel & Mixture mass Axial Profile

SSTEEL mass in core channels  MIXTU mass in core channels

1730K S. Steel melting

degradated materials: (COMPACT or CRACKED) → (DISLOCAT).
Total S.Steel mass Development

SSTEEL mass in the core

~ 1.5 Kg S. Steel melting
Quench Phase

Temperatures profile CLADs

1. CLAD1
2. CLAD2
3. CLAD3

Core field - void fraction
Calculation End

Temperatures profile CLADs

1. CLAD1
2. CLAD2
3. CLAD3

Core field - void fraction
SUMMARY

• The present ASTEC version can be used to simulate BWR bundle test. In order to simulate the radiative heat exchanges between bundle rod and square channel box wall (e.g. Canister wall of BWR assembly), the square box should be modelled as cylindrical geometry.

• “Cruciform control blade”: Present version can be applied for BWR case by modelling the rectangular blade as equivalent cylinders.

• The simulation results show ASTEC can give reasonable results. The results was used to support experimental staffs to design experiment progress.

• OUTLOOK: post-test calculations.
First information on QUENCH-20- bundle test

Electrical power profile during QUENCH-20 and readings of three selected thermocouples installed at cladding surface (TFS), shroud (TSH) (both at the hottest elevation of 950 mm) and at the absorber blade surface at the elevation of 450 mm.