Ageing Management of Baffle Former Bolts in Belgian Nuclear Power Plants

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Introduction

- 7 Belgian PWR Nuclear units operated by Electrabel (ENGIE)

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<td>1008</td>
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<td>Doel 1</td>
<td>433</td>
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Nuclear Power Plants account for ~50% of the electrical production in Belgium
Core barrel, baffle and former plates
  - Type 304 austenitic stainless steel

Baffle bolts
  - Attach the baffle plates to the former plates in the vessel internals
  - Type 316 cold worked austenitic stainless steel

In most recent configurations (Doel 3-4 and Tihange 2-3)
  - Cooling hole in former plate in front of the shank of each baffle bolt
  - Ensure the cooling of the bolt shank

Tihange 1 and Doel 1-2: no cooling holes
**Design**

- **Doel 1-2 (2 loops 390 MW – uprated to 433 MW)**
  - Downflow
  - Core height = 8 feet (2440 mm)
  - 5 formers
  - Baffle plate thickness = 28,6 mm
  - 536 Baffle bolts - 868 Edge bolts

- **Tihange 1 (3 loops 900 MW)**
  - Initially downflow, converted upflow in 1986
  - Core height = 12 feet (3660 mm)
  - 8 formers (comparable spacing to Doel 1-2)
  - Baffle plate thickness = 22 mm
  - 1088 Baffle Bolts - 244 Edge bolts
Degradation Mechanisms
Degradation mechanisms

- **Main Problem** = Cracking of baffle bolts in the baffle-former assembly
  - First observed in 1989 in French units of the CP0 series
  - Cracked bolts discovered in 1991 in Tihange 1 (very similar to the CP0 units)
  - Phenomenon also observed in a few other units (USA, Japan and other countries)

- **Potential irradiation swelling of the baffle and former plates and of the baffle bolts**
  - No known occurrence of significant irradiation swelling in any operating PWR up to now
  - Remains a concern in case of long term operation (> 40 years)
Degradation mechanisms

● Potential consequences of the baffle bolts degradation

  — Deformation of baffle plates due to the pressure gradient between the baffle and the core
    -> downflow configuration : baffle jetting

  — In case of LOCA, baffle plates are subjected to significantly higher pressure gradients than in steady-state regime -> successive failure of bolts on the same plate and deformation of the baffle plate

  — Actually the number of bolts is significantly higher than the number required for assuring the integrity of the baffle-former assembly in the most severe loading conditions

● No unacceptable degradation of baffle and former plates detected in the world

  — A lot of experience feedback about cracking of baffle bolts
Baffle-Former Bolts status in Belgian units
Baffle-former bolts status in Tihange 1 (inspections & replacements)

- 1991-1992 inspections by UT and VT: 19 cracked bolts, 16 uncertain, 35 non-controllable
  - 5 bolts replaced in 1992
- 1995: full inspection by UT and VT (960 bolts): 37 cracked bolts, 54 “non-interpretable”
  - Replacement of those 91 bolts
  - After reevaluation of the inspection results (ultrasonic scans) in 2003:
    27 cracked bolts (instead of 37), 6 non-interpretable (instead of 54)
  - With new evaluation, Tihange 1 falls back in line with the French CP0 units behavior
- 2002: full inspection by UT and VT (960 bolts):
  - 5 cracked bolts, 1 non-interpretable (less than could be expected from extrapolation of past results)
Baffle-former bolts status in Tihange 1 (inspections & replacements)

- 2010: full inspection by UT and VT (960 bolts)
  - Acceleration of the degradation kinetic, 23 additional cracked bolts, mainly in the lowest row

- 2011: replacement of the 29 defective bolts and 13 additional bolts necessary to ensure structural integrity until 2014

- 2014: full inspection by UT and VT (960 bolts) and mobilization of the replacement tool
  - 1 defective bolt on the lower former (already present in 2010 but that could not be replaced)
  - 5 non-interpretable bolts on the lower former (2 already present in 2010)
  - Conclusion: Only 3 additional non-interpretable bolts between 2010 and 2014
Baffle-former bolts status in Tihange 1 (inspections & replacements)
Baffle-former bolts status in Doel 1 (inspections & replacements)

- 1991: inspection by UT and VT: No cracked bolts

- 2005: full inspection by UT and VT (536 bolts): 8 bolts with indications on short baffle plates
  – 7 on elevation D (4\textsuperscript{th} former from the bottom) in symmetrical positions and 1 on elevation A (lower former)
  
  — 10 bolts replaced: those 8 bolts with indications, 1 bolt in symmetrical position to the 7 defective bolts and 1 high dose bolt (47 dpa) for analysis
Baffle-former bolts status in Doel 1 (inspections & replacements)

- 2015: full inspection by UT and VT (536 bolts): 5 bolts with indications, all located on the lower former in the same symmetrical positions as the cracked bolts identified on the former D in 2005

  - Replacement of 7 bolts: those 5 bolts with indications + 2 bolts in symmetrical positions (the 8th bolt in symmetrical position was already replaced in 2005)
Baffle-former bolts status in Doel 2 (inspections & replacements)

- 2006: full inspection by UT and VT (536 bolts) – 1st inspection:
  - 6 bolts with indications distributed on different former plates but on the same short baffle plates where defective bolts were found in Doel 1:
    - 1 in rows 1, 2, 4 and 5 (formers A, B, D and E)
    - 2 in row 3 (former C)
  - 14 bolts replaced:
    - those 6 bolts with indications,
    - 7 bolts in the same position as the 7 symmetrical ones found on former D in Doel 1 in 2005
    - 1 short bolt (installed in a position where a long bolt was required)
Baffle-former bolts status in Doel 2 (inspections & replacements)

- 2015: full inspection by UT and VT (536 bolts):
  - 3 bolts with indications + 4 non-inspectable bolts distributed on different former plates but on the same short baffle plates where defective bolts were found in Doel 1:
    - 1 in row 1 (former A)
    - 2 in row 2 (former B)
    - 2 in row 3 (former C)
    - 1 in row 4 (former D)
    - 1 in row 5 (former E)
  - Replacement of those 7 bolts
Main differences between configurations in Tihange 2-3 and Doel 3-4 vs. Tihange 1 / Doel 1-2

- Cooling holes in the formers -> water flow and cooling around the shaft of the baffle bolts
- Upflow configuration from commissioning
- Formers are regularly spaced. It is not the case in Tihange 1, where they are more widely spaced in the lower part -> higher stresses in the baffle bolts
- Design of the baffle bolts -> parabolic geometry of the radius at the head-shank junction

Inspections

- 2012: full inspection by UT and VT in Doel 3 (960 bolts) at the 3rd 10-year outage: no indications found
- Planned in September 2016: partial inspection (~1/3 of the 1080 bolts) by UT and VT in Tihange 3 (scope based on the location of cracked bolts in Tihange 1 and French CP0 units)
- Planned in Spring 2017: full inspection by UT and VT in Doel 4 (1080 bolts)
IASCC of Baffle-Former Bolts in Tihange 1 and Doel 1 & 2
Determination of the fluence, temperature and stress distribution in Tihange 1

- Lowest dose for the 8th (upper) former, intermediate doses for the 1st (lower) and the 7th formers
- Shape of the temperature distribution very similar to the fluence distribution
- Reasonable correlation of the cracked bolt locations with zones of high dose and high temperature. More complicated in reality.

Dose distribution

Cracked bolts distribution
Determination of the fluence, temperature and stress distribution in Doel 1 & 2

- High dose bolt (47dpa at 12.5 mm from head surface) confirmed as defect free

- Dose on Doel 1 cracked bolts: 12 to 13 dpa at head to shank junction
Temperature analysis for Doel 1 & 2 and Tihange 1 configurations

- Combination of global and local models
- More favorable situation in Doel 1-2 as compared to Tihange 1
  - Smaller holes close to the baffle plates instead of large holes in the central part of the former
  - Max $T^\circ$ at the head-shank junction: 340°C in Doel 1-2, 370°C in Tihange 1
  - Max $T^\circ$ at the baffle-former corner: 375°C but smaller affected volume in Doel 1-2
Investigations on extracted baffle-former bolts Doel 1 & 2
The intergranular nature of the cracking is confirmed

Outer and rupture surfaces covered with corrosion products

Cracking starts at the head-shank junction of the bolt, where stresses are more important
Characterization of baffle-former bolts extracted from Doel 1-2 by SCK.CEN (Belgian Nuclear Research Center)

- Details of corrosion products on the fracture surface (~ 12 dpa at the crack location)
Characterization of baffle-former bolts extracted from Doel 1-2 by SCK.CEN (Belgian Nuclear Research Center)

- Tensile tests

![Tensile stress-strain curve](image)

- Room temperature
  - T1: 12.3 dpa
  - T2: 7.9 dpa
- 300°C
Characterization of baffle-former bolts extracted from Doel 1-2 by SCK.CEN (Belgian Nuclear Research Center)

- Tensile tests
  - Ductile fracture mode in all specimens
Characterization of baffle-former bolts extracted from Doel 1-2 by SCK.CEN (Belgian Nuclear Research Center)

- Fracture toughness tests
  - Disc shaped Compact specimens (DCTs) (Ø 13.5 mm) made from the cross section of the baffle bolts shank
  - 1 set of specimens of 10-15 dpa + 1 set of specimens of ~ 60 dpa
Characterization of baffle-former bolts extracted from Doel 1-2 by SCK.CEN (Belgian Nuclear Research Center)

- Fracture toughness tests

10-12 dpa: 
$K_{Jc} = 58$ to 105 MPa√m

59 dpa: 
$K_{Jc} = 54$-70 MPa√m

Fracture toughness of irradiated stainless steels in nuclear power systems, S.Fyfitch et al., 14th Int. Conf. on Environmental Degradation of Materials in Nuclear Power Systems, Virginia Beach, VA, August 23-27, 2009
Irradiation swelling
Irradiation swelling

- **Tihange 1 baffle bolts**
  - Withdrawn in 1995 (Battelle Pacific Northwest Laboratory, CIR program)
    - Different positions examined along the bolt length and estimation of the corresponding swelling
    - Highest swelling of 0.24% measured at 55 mm from the bolt head surface (not at the highest dose location which is close to the head surface)
    - Cavities: Ø 7-8nm
  - Withdrawn in 2011 (SCK.CEN) – Preliminary work in progress
    - Cavities: Ø up to 6nm, swelling: max. 0.06%

- **Doel 1-2 bolts (SCK.CEN)** withdrawn in 2005
  - Some cavities in the baffle bolts of Doel 1-2: smaller size (2.5 nm) as compared to Tihange1 bolt and negligible swelling
Interactions between neutron dose, dose rate and temperature on the swelling incubation time and swelling rate are complex.

No reliable and validated swelling prediction model for PWRs is currently available.

Irradiation swelling does not represent a significant risk for 40 years of operation but remains a potential issue in case of long term operation.

Better assessment of the risk of long-term swelling: ENGIE participates in the GONDOLE international irradiation program in the Osiris reactor at CEA (CEA-EDF-AREVA-EPRI-ENGIE).

Materials from Doel 1 locking bar, (62 dpa) Doel 1-2 baffle bolts (8 to 36 dpa), Tihange 2 thimble tube (40-80 dpa) being re-irradiated for up to 30 additional dpa.
Mitigation and Repair

- Possibilities to mitigate the degradation are rather limited:
  - FLUENCE: Difficult to reduce and of limited use though the already high dose in the internals
  - TEMPERATURE: Practical possibilities are limited and must be implemented at the design stage
  - UPFLOW CONVERSION:
    - Decrease $\Delta P$ between the two sides of the baffle plates (and the risk of baffle jetting)
    - Decrease forces on the bolts
    - Implemented in Tihange 1 in 1986, initial design for Tihange 2-3, Doel 3-4
    - No conversion planned in Doel 1-2 at the present time

- The only repair technique presently applicable: replacement of the baffle bolts
Mitigation and Repair

- Replacement of the baffle bolts – options:
  - Full replacement (performed in some Japanese PWRs)
  - Systematic replacement (roughly 1/3 of the bolts necessary for structural integrity)
  - Replacement of the cracked bolts only (done in Belgium)

- Design improvements on replacement bolts
  - Modification for the head to shank radius to reduce stress concentration
  - Reduction of tightening torque
  - New mechanical locking mechanism to avoid welding on the irradiated baffle plates
  - Same material is used: cold worked 316 stainless steel
Conclusions
Conclusions

- Main degradation mechanism of baffle-former assembly is IASCC of the baffle bolts.
- Most susceptible units are the oldest ones (>30 years of operation) due to the design and higher accumulated doses.
- Degradation mechanisms and influence of the fluence, temperature and stress are not yet fully understood.
- Occurrence of very limited void swelling in Tihange 1.
- Replacement of affected bolts by bolts with improved design was performed in Tihange 1 and Doel 1-2.