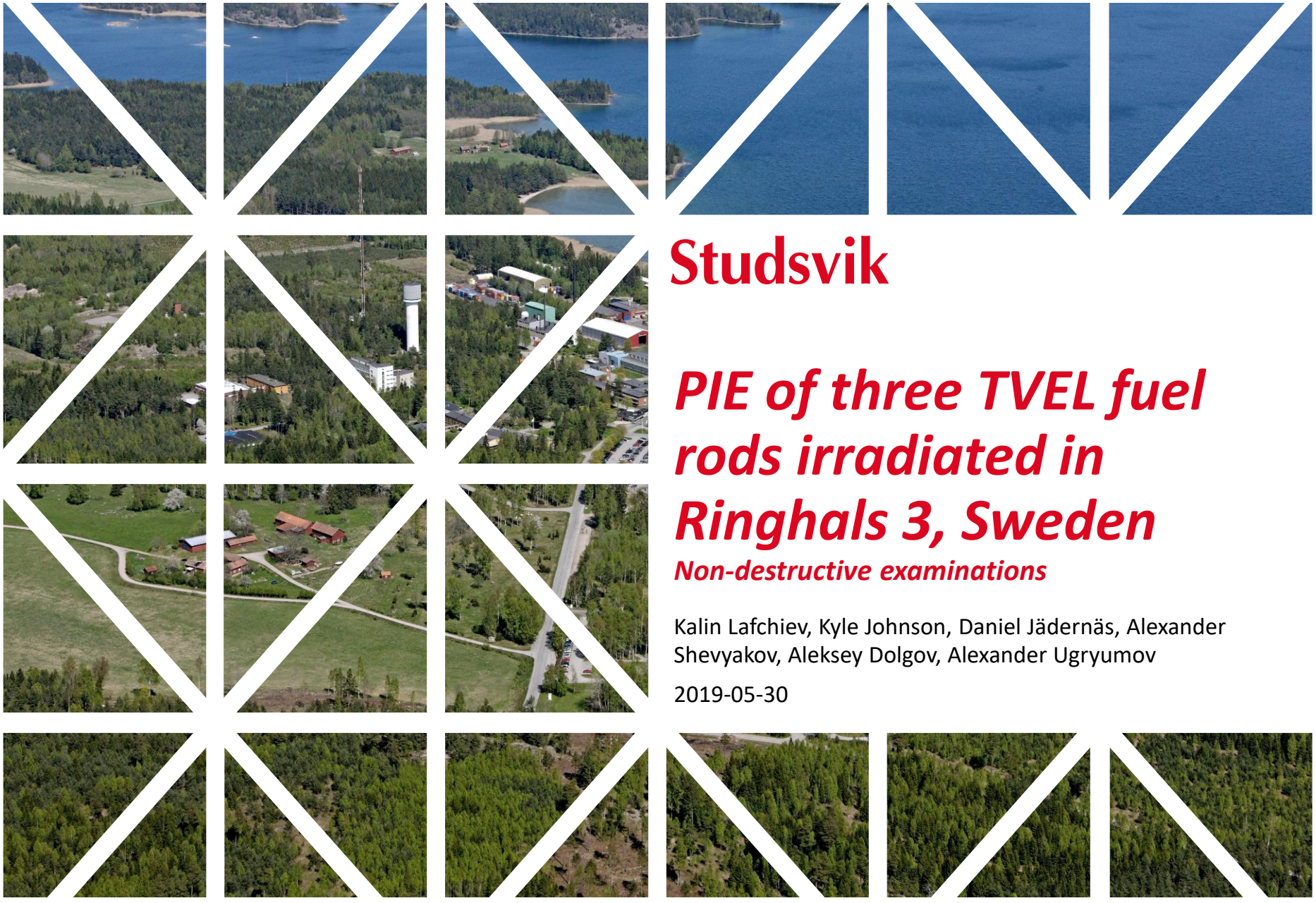

Studsvik

PIE of three TVEL fuel rods irradiated in Ringhals 3, Sweden

Non-destructive examinations

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INTRO

- Three TVEL fuel rods were transported to Studsvik Hot Cell Labs (HCL) in November 2018 for PIE.
- An extensive scope of non-destructive (NDE) and destructive examinations is ongoing in Studsvik

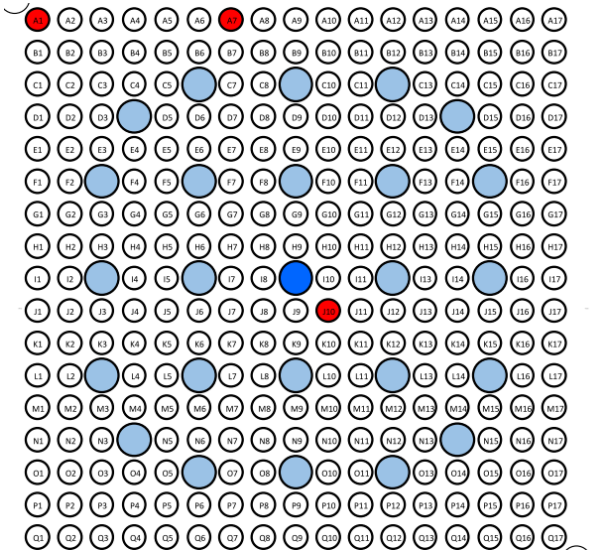
- Main purpose of the examinations: to support the licensing of PWR fuel in US, Europe and Asia

- Results from the NDE will be presented in this presentation

FUEL RODS IRRADIATION

- The rods were irradiated in Ringhals Unit 3 for three irradiation cycles to an average burnup of ca 40 MWd/kgU

- The fuel rods have been positioned in the same assembly (0AM3) and were designated in accordance to their position in the assembly, respectively A1, A7 and A10



	Average Linear heat generation rate [W/cm]		
Cycle	A1	A7	A10
c32	217.68	214.96	203.54
c34	168.83	158.08	220.99
c35	235.02	235.94	236.58

Average burnup [MWd/kgU]		
A1	A7	A10
40.3	41.7	42.6

FUEL ROD NOMINAL DATA

- Fuel rod length – 3852 mm
- Cladding type – E110opt
- Cladding outer diameter - 9.5 mm
- Cladding thickness – 0.54 mm

- Fuel stack length – 3660 mm
- Fuel type – UO_2
- Pellet length – 12 mm
- Enrichment – 4.417 %

LIST OF NDE

- Puncturing and fission gas analyses
- Fuel rod cutting
- Length measurements
- Visual inspection
- Gamma scanning and burnup evaluation
- Profilometry
- EC-Oxide thickness measurements

All equipment in Studsvik HCL is designed to handle approximately 1 meter long segments. Therefore puncturing and cutting are considered as part of the NDE

PUNCTURING AND FISSION GAS ANALYSES

- The rods were punctured in the plenum
- Rod internal volume and pressure was measured
- Generated fission gas calculated with ORIGEN
- Collected gas samples analyzed with gas mass spectroscopy

Puncturing data	A1	A7	J10
Rod internal volume [cm^3]	12.77	12.88	12.67
Rod pressure at 0 °C [MPa]	3.02	3.02	3.24

Fission gas releases	A1	A7	J10
Kr gas release [%]	0.44	0.56	1.72
Xe gas release [%]	0.5	0.63	1.81

CUTTING AND FUEL ROD LENGTH MEASUREMENTS

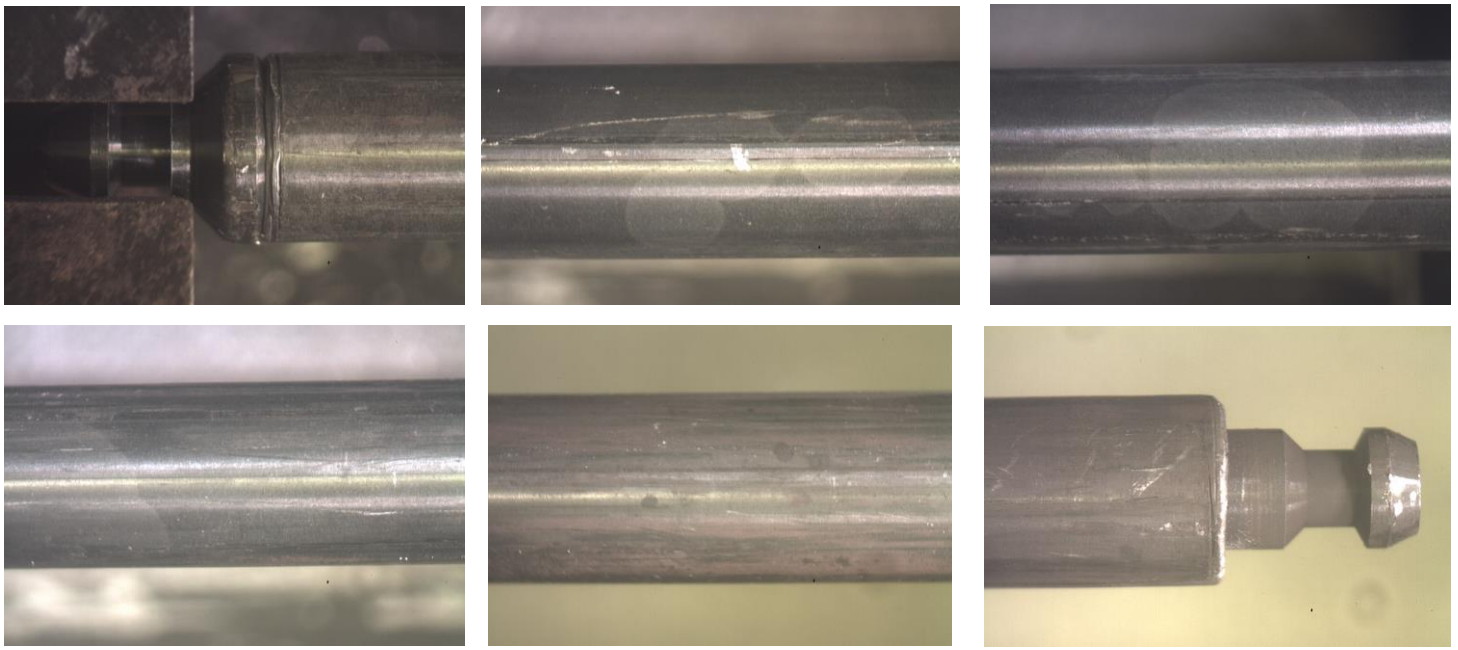
- Cutting was performed with tube cutter
- Full length rod was cut in 4 segments taking into consideration the spacer grid positions
- A periscope equipment and a motor driven fixture with a Sony scale measurement device were used for the length measurements.
- The individual lengths of four segments belonging to one rod were measured and the lengths for the four segments were summed to the total rod length.

Rod	Length (mm)	Segment 1 (mm)	Segment 2 (mm)	Segment 3 (mm)	Segment 4 (mm)
A1	**3870.2**	705.5	1059.1	1043.7	1062.0
A7	**3870.5**	705.1	1058.9	1044.3	1062.3
J10	**3869.8**	705.5	1057.7	1044.0	1062.7

The fuel rod growth from the nominal length (3852 mm) is lower than 0.5 %

VISUAL INSPECTION

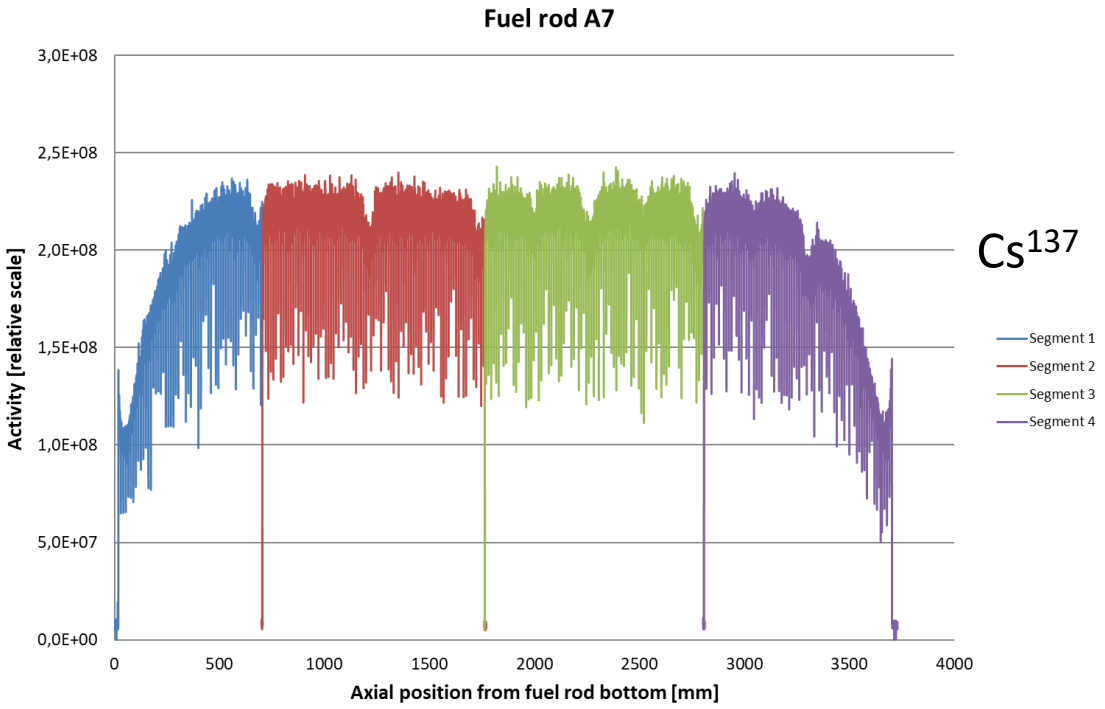
- Entire surface of the fuel rods was inspected using periscope equipment
- Representative images taken with digital camera



- Generally the rods looked good
- Some scratches from insertion/extraction and some handling marks were observed
- ”The leopard” appearance was present
- No spacer fretting marks observed

GAMMA SCANNING

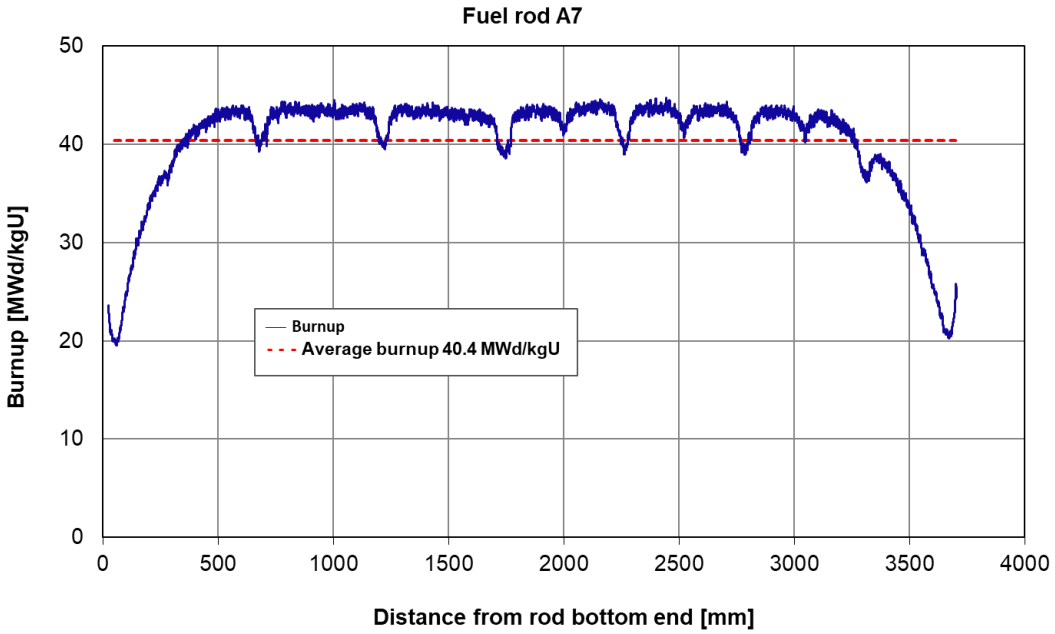
- The gamma scanning was performed using a germanium detector and a 0.1 mm collimator. Axial steps 0.25 mm.
- Fuel stack length measured from Cs^{137} activity profile



Rod	Fuel stack length (mm)	Elongation [%]
A1	**3687.75**	**0.8**
A7	**3684.50**	**0.7**
J10	**3690.25**	**0.8**

BURNUP EVALUATION

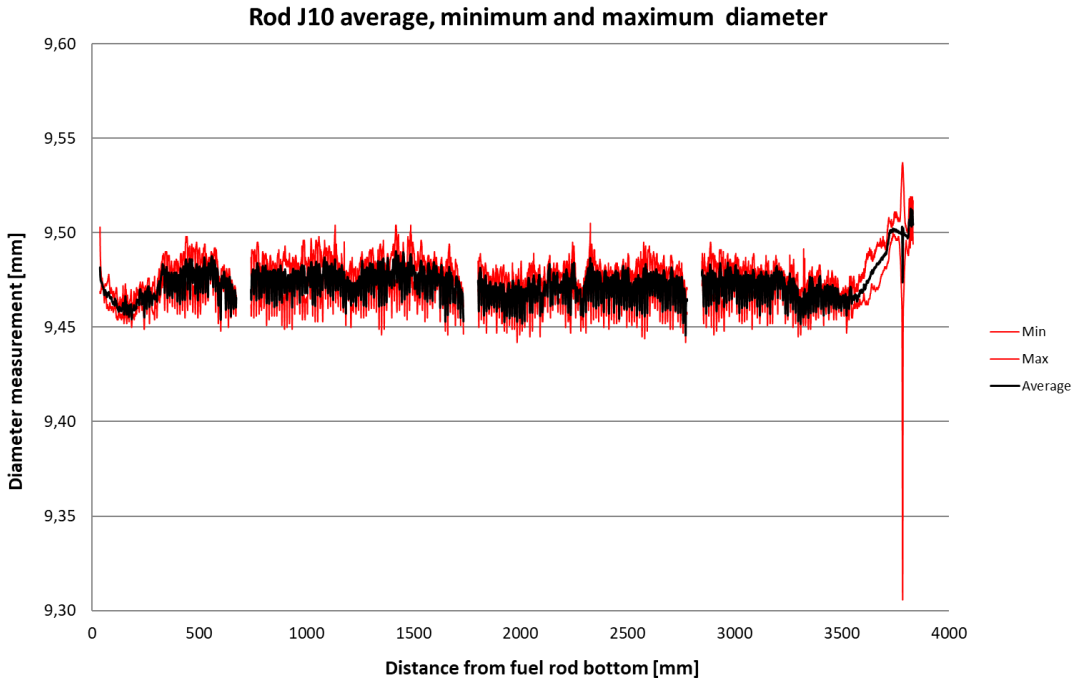
- Cs^{137} activity profiles were used for local burnup evaluation
- Fuel rods were gamma scanned together with a reference rod
- Burnup of the reference rod has been determined by several independent laboratories using the Nd-148 method
- The burnup is obtained by applying correction factors using data for the reference and examined rods



	Burnup [MWd/kgU]		
Rod	Ringhals average	GS average	GS local max
A1	40.3	38.0	41.7
A7	41.7	40.4	43.4
J10	42.6	42.0	45.9

PROFILOMETRY

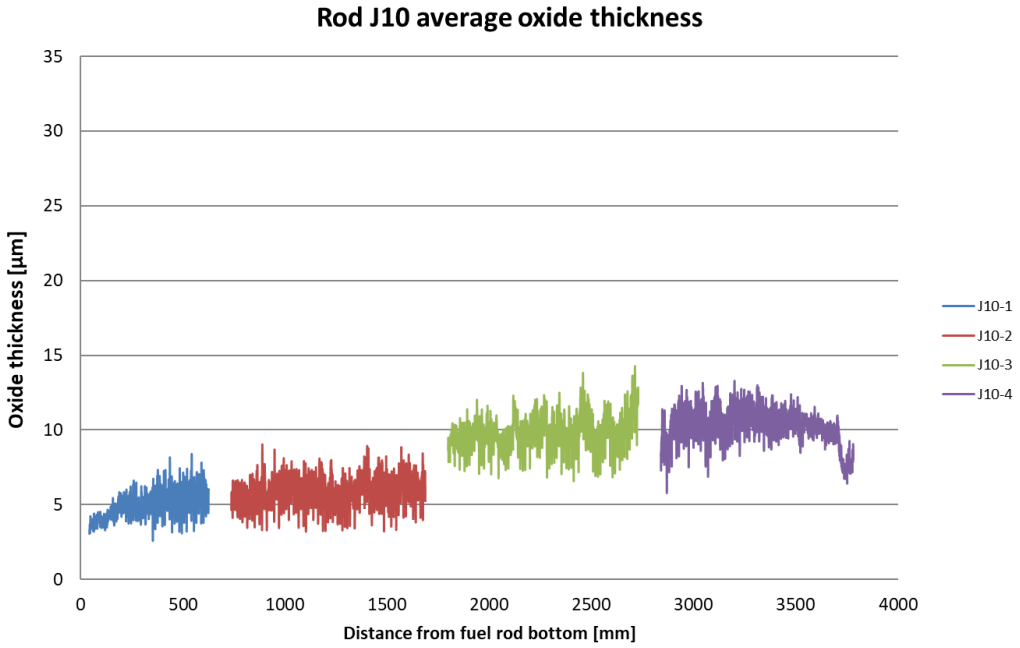
- A vertical profilometer rig was used
- The diameter is measured along four orientations (0-180°, 45-225°, 90-270°, 135-315°)



- Average diameter – 9.46 – 9.47 mm

OXIDE THICKNESS MEASUREMENTS

- Measured by eddy-current method



- Thin oxide – from 5 µm at fuel rod bottom to 10 µm at fuel rod top

SUMMARY

- Three TVEL fuel rods irradiated in Ringhals 3 to a burnup of ca 40 MWd/kgU are under examination in Studsvik Hot cells
- FGR 0.5-0.6 % for the periphery rods A1 and A7 and 1.8 % for the central rod J10
- No spacer grid fretting marks present
- The fuel rod growth was lower than 0.5 %
- Fuel stack elongation was 0.7-0.8 %
- Fuel rod average diameter – 9.46 – 9.47 mm
- Fuel rod oxide thickness 5 µm -10 µm

FUTURE WORK

- Gap measurements
- Metallography and ceramography by LOM
- SEM EPMA on the fuel
- TEM on the cladding
- Fuel density measurements
- Hydrogen content measurements
- X-ray diffraction analyses
- Mechanical testing – Axial and ring tensile tests, fatigue tests
- Hardening relaxation tests
- Creep testing under internal pressure
- Refabrication of fuel segments for ramp tests

THANK YOU!!!