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JHR irradiation devices: Inspection Methods proposal

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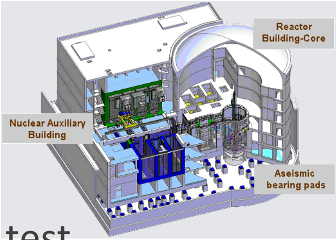

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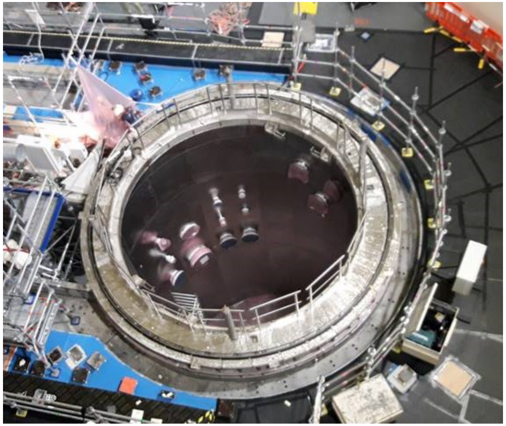
❑ JHR context

- The Jules Horowitz Reactor which is currently under construction at the CEA Cadarache centre (South of France) is a Material Testing Reactor (MTR).
- It will be used to perform irradiation tests on Fuels and Materials samples as part of support programmes for current Nuclear Power Reactors (Gen II and III) and future Reactors (Gen IV and fusion).
- This reactor will also be used to produce radioelements (mainly Mo-99) for medical purposes and will meet 50% of the European demand in this field.



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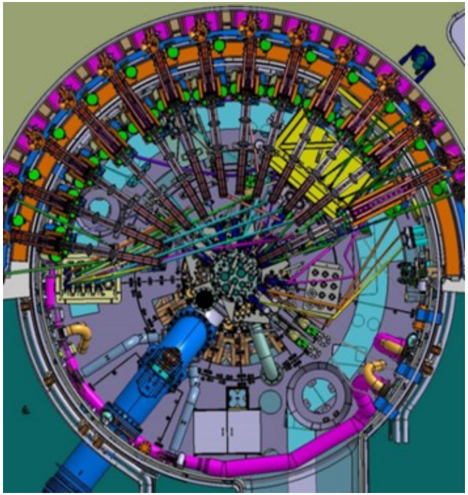
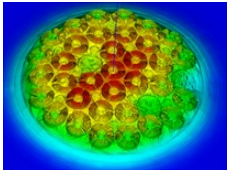
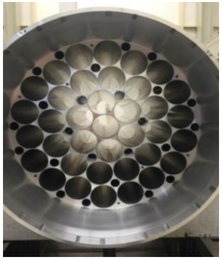
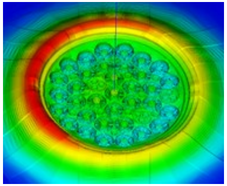
❑ JHR main characteristics



- ✓ Compact core: designed to generate
  a nominal power up to 100 MW_{th}
- ✓ Cylindrical in shape
  with a diameter of 60 cm and a height of 60 cm
- ✓ Reactor immersed
  under 9.3 m of water in a 12 m deep pool
- ✓ Under-moderated core
  in order to generate strong fast neutron fluxes
  up to 5.10^{14} $cm^{-2}·s^{-1}$, E > 1MeV
- ✓ Primary system: closed and slightly pressurised
  12 bar upstream of the core
- ✓ Cooling water in the core flows upwards
  at a velocity of about 10 m/s
- ✓ Gamma heating in the core:
  about 15 to 20 W/g (maximum local value)
- ✓ Beryllium reflector: 30 cm thick and around the core vessel
- ✓ Thermal neutron flux in the reflector $3·10^{14}$ $cm^{-2}s^{-1}$)







❑ Periodic inspections of the JHR irradiation test devices

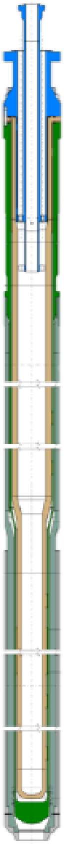
- JHR irradiation test devices fall into N2 class of French nuclear pressure equipment regulation.

- Inspection interval of the devices is 40 months (French ESP(N) Regulation rules).

- The inspection must be performed using non-destructive methods.

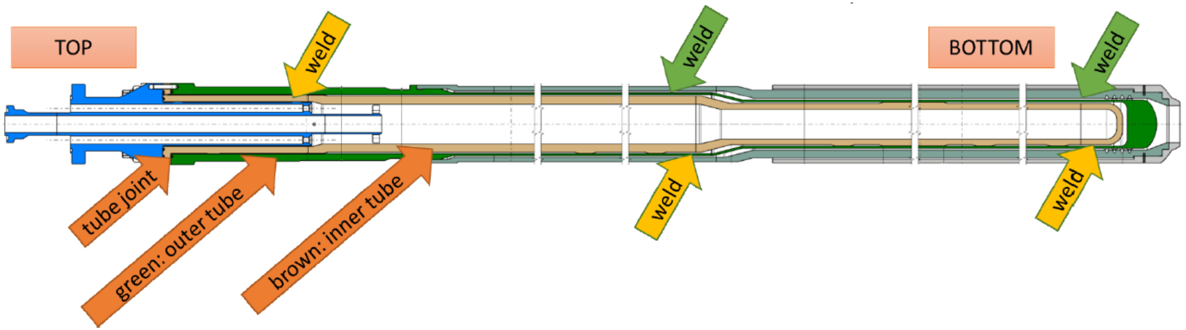
- This study was centered on ADELINE device and the examination the possible methods and locations that could be utilized.

- This initial study was performed in collaboration between VTT Technical Research Centre of Finland Ltd and CEA . It was performed as VTT employee secondment at CEA Cadarache from October 2019 to March 2020.



❑ ADELINE irradiation test device

- The device consists of two nested vertical tubes with under a millimeter of separation.
- Once used, the tubes cannot longer be separated (thermal and irradiation deformation).
- Tubes are joined at only one location.
- Both tubes have multiple internal welds that are a special interest in periodical inspections.



❑ Inspection resolution

- Irradiation test devices will be built according to RCC-MRx code:
  - "Design and Construction Rules for Mechanical Components in high-temperature structures, experimental reactors and fusion reactors"
  - Intended for construction phase and thus does not offer direct advice to periodic inspections and does not cover corrosion.

- However, it does specify that no crack type defects of any size are allowed.

- What is the required inspection resolution is not explained RCC-MRx. For the purposes of this study, it was assumed that:
  - cracks smaller than 0.2 mm do not need to be detected
  - corrosion layer thickness is 0.05 mm

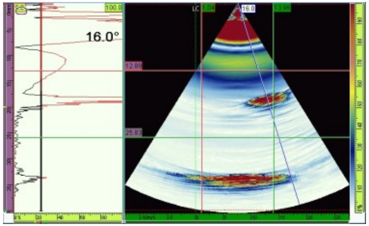
N°	Imperfection designation	EN ISO 6520-1 N°	Within thickness	Class N_2Rx
1	Crack	100	t ≥ 0.5 mm	**Unacceptable**
2	Crater crack	104	t ≥ 0.5 mm	**Unacceptable**

❑ Possible inspection methods

- Multiple non-destructive methods are available but it was not possible to focus on all of them. In this first stage, focus was directed to ultrasonic and eddy current methods. Later, the focus was further directed into volumetric ultrasonic and eddy current surfaces can types of inspections.

- Ultrasonic guided waves were not studied as this would have been a too lengthy study.

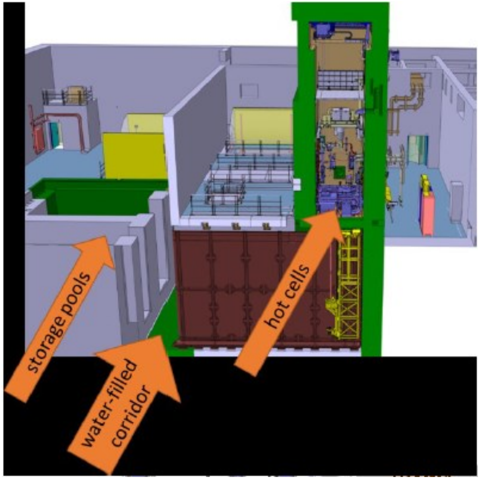
- The discussed methods are listed on the right. The final two methods of focus are underlined. This focus of interest didn't imply that the other methods have been ruled out.



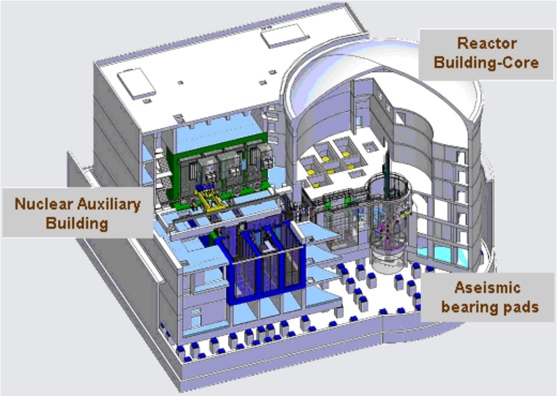
- Ultrasonic
  - <u>Volumetric</u>
  - Guided waves
- Eddy current
  - <u>Surface (perperdicular to the object)</u>
  - Bobbin probe (cylindrical)
- X-rays
- Visual inspection
  - Dye penetrant
  - (In 2021 project it is assumed than an initial visual inspection will be made in the hot cell)

❑ Location of inspection operation

- Once the test device is removed from the reactor core, the sample holder of the device can be removed at the reactor pool. From there the device will be transported to the hot cell for disassembly of the internal apparatus. Possible periodic inspection locations are the hot cell and the storage pool (EPI) near the hot cell. Both locations are accessible with existing transportation means.



- The storage pool is likely a better option as inspection in a hot cell would mean non-submerged inspection in a place where space is premium, whereas inspection in a storage pool would take place underwater and in an area where a dedicated inspection rig can be constructed.



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❑ Execution of the inspection

Inspection will need to be performed for both the inner and the outer tube. How the device and the probe would be handled was not studied in detail but one possibility is the following:

Outer tube inspection:
- Device remains vertical and will be rotated. The probe is introduced to the device radially from the side.
- Probe is capable of being moved vertically and radially in relation to the device.

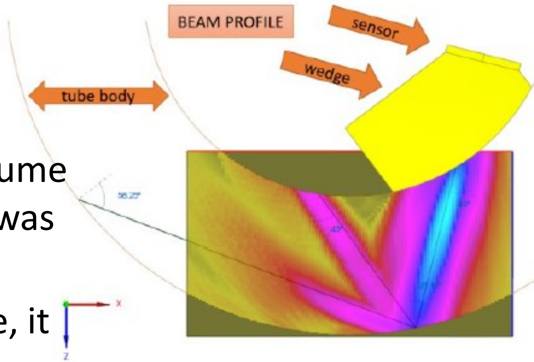
Inner tube inspection:
- A manipulator arm is inserted into the device which remains vertical. It is capable of moving vertically and radially in relation to the device.
- Either the manipulator arm or the device is rotated.

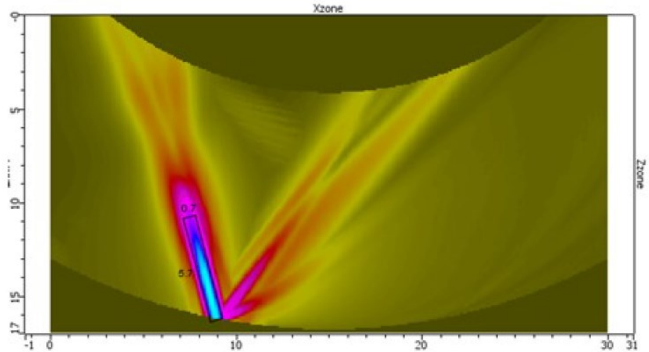
❑ Sensors used in the ultrasonic simulations

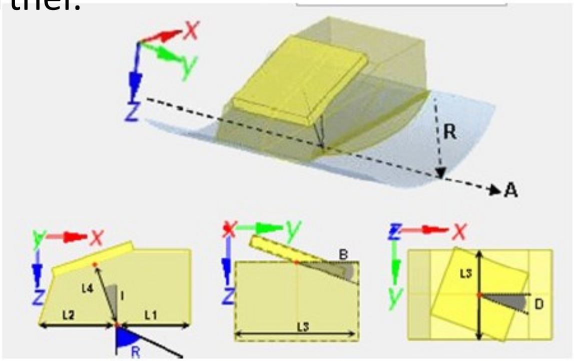
Two ultrasonic sensors of typical frequency (2 and 10 MHz) were used in the first scoping calculations.

Beam profiles and the behavior in the tube volume was observed and the effect on the inspection was discussed.

As experimental reference was not yet available, it was not possible to asses the probe types further.







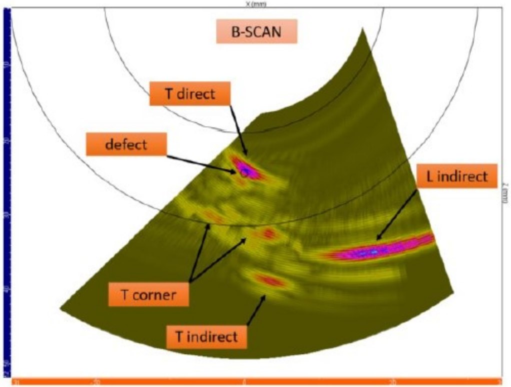
❑ Ultrasonic echo identification

CIVA NDE 11

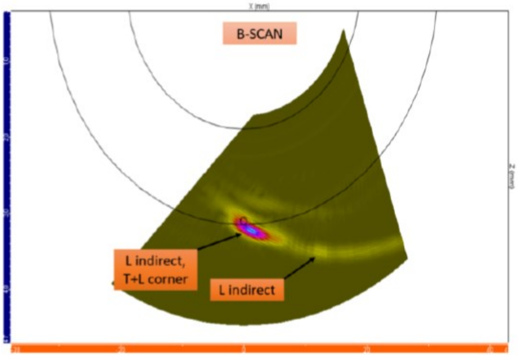
T	transversal wave
L	longitudinal wave
SDH	side drilled hole
direct	direct echo from the defect
corner	path includes the defect and one back wall reflection
indirect	path includes the defect and two back wall reflections

Many echoes can be present in the examination, CIVA simulations can help to predict and identify them.

1 mm Side Drilled Hole at 5 mm depth.
A multitude of echoes is present. →

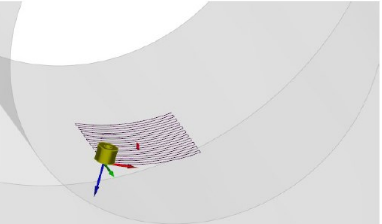


1 mm Side Drilled Hole at back wall.
Corner echo is the strongest. →



❑ Eddy current lift-off parametric variation

A reasonable assumption as a sensor was identified and parametric variations of sensor lift-off were performed.



Sensor lift-off was varied from 0 to 1.8 mm.

Rectangular vertical surface defect sizes ranged from 0.5 mm to 0.05 mm.

Lift-off [mm]	Amplitude [nV] 0.5x0.5x0.1 mm defect	Amplitude [nV] 0.2x0.2x0.1 mm defect
0	913881	192506
0.2	354888	65249
0.4	210561	37951
0.6	96467	17264
0.8	56365	10090
1	27977	4967
1.2	15795	2792
1.4	9497	1639
1.6	6136	1060
1.8	4382	759

Background noise of close-to-sensor electronics is approximately 1 nV. This will impose a detection threshold for defect responses.

All of the simulated defect response amplitudes are above 1 nV. This is promising but experimental reference is needed for conclusions.

Lower lift-off is better but what is mechanically achievable will be discovered later.

❑ Conclusions of the first 6 month stage (2019-2020)

The conclusions of the initial study are the following:

• Two inspection methods are likely needed: Eddy current is likely suitable for surface examination while volumetric ultrasonic inspection can be used for tube bodies.

• Inspection under-water in a storage pool is likely the best option for location.

• Some automation and remote control is needed in the inspection process as the inspection area is quite large (tubes are close to 4 m long).

• Internal surfaces located between the nested tubes likely cannot be inspected for corrosion and therefore, sealing the space from oxygen and water is likely the best option.

• A study should be made on the existing sensors: availability at CEA, suitability for the first experimental phase and the possible need for a sensor design process.

Experimental testing is now a critical next step in order to assess and qualify the inspection methods.

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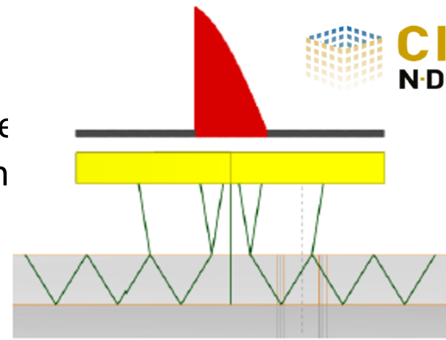
❑ Continuation of the inspection project (2021)

Samples of the test device inner and outer tubes have been manufactured and artificial defects are being machined. These are the focus of the new continuation project.

Φ_e88mm e4mm L110mm and Φ_e58mm e8mm L108mm

Probe characteristics for their inspection have been decided (Linear phased array 15MHz). Defects will be machined into the samples, VTT will make an inspection plan for the samples and perform CIVA simulations. CEA will then proceed to perform the needed experimental tests.



0° longitudinal wave, ±45° transversal wave, full skip to scan both ID and OD surfaces.

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