In Service Inspection and Repair Developments for SFRs and Extension to other Gen4 Systems

Dr. Francois Baqué, CEA, France

24 June 2021

Meet the Presenter

Dr. Francois Baqué works as a Senior Expert on inspection for fast reactors at CEA Cadarache IRESNE in the Nuclear Technology Department.

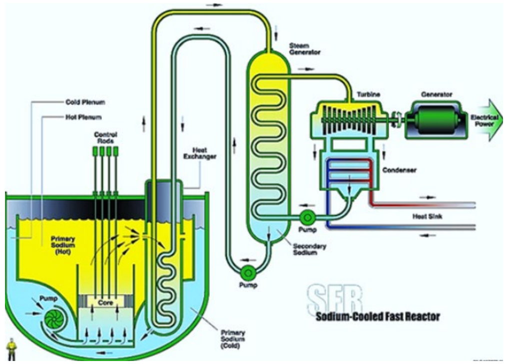
He was the manager of R&D activities associated to In Service Inspection and Repair for ASTRID Project at CEA (2010-2019). In this frame, he was the leader of CEA staff acting for the development and qualification of ultrasonic and electromagnetic sensors and related inspection methods.

Presently, he supervises PhD works on ultrasonic methods with French University and National Centre for Scientific Research. He is an active participant to the Gen4/SFR-CD&BOP (Component Design and Balance of Plant) group for inspection systems and methods.

He published number of papers on associated studies and participated in the relevant international conferences (ICAPP, FR, ANIMMA…). He was a former manager of the French Sodium School (2004-2010) who developed international activities.

Email: Francois.Baque@cea.fr

CONTENT



Sodium Fast Reactors (SFRs)

Main objectives for Non Destructive Examination (In Service Inspection)

NDE and ISI Techniques developments

- Sensors: under sodium ultrasonic sensors
- Methods: under sodium Non Destructive Examination, Telemetry and Imaging

Inspection demonstration for some SFRs configurations

- Under sodium telemetry and vision within the reactor block
- Under sodium Non Destructive Examination of welded joints within the core support structure
- NDE of welded joints, from outside primary sodium (through main vessel wall)

Intervention in liquid sodium: tightness, robotics

- In-sodium tightness
- In-sodium robotics

Extension to other Gen4 Systems: LFR, SCWR, VHTR, GFR, MSR

Conclusion and Perspectives

SFRs Objectives as Regards to Generation IV Frame

➔ A GEN IV system

Safety :
- Level at least equivalent to GEN III systems
- Progresses on Na reactors specificities
- Integrating FUKUSHIMA accident feedback
- Robustness of safety demonstration

Durability
- Need of Fast Breeder Reactors and a closed cycle
- Pu multi recycling to preserve natural resources
- The use of natural depleted uranium in France by FBRs allow producing electricity for few thousands of years

Operability :
- Load factor of 80% or more after first "learning" years
- Significant progress concerning In Service Inspection & Repair (ISIR)

Ultimate wastes transmutation :
- Realization of demonstrations on minor actinides transmutation according to June 28, 2006 French Act on Wastes Management

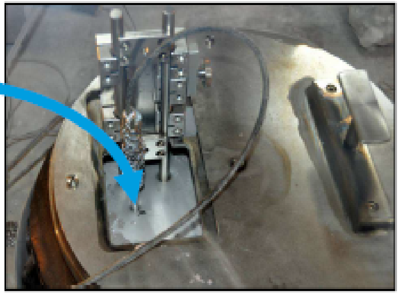
A mastered investment cost

Non proliferation warranty

In Service Inspection with Non Destructive Examination Techniques

Relevant Characteristics for Examination and Inspection of SFRs

Using sodium as coolant implies some specificities :



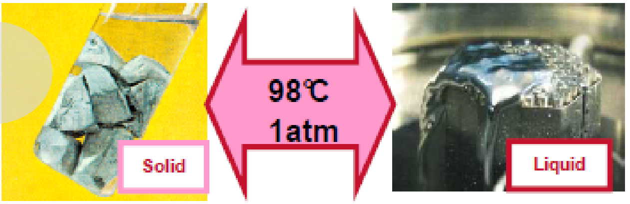
Opacity

- Optical devices cannot be performed
- Only ultrasonic devices are suitable under the free level

→ Development and mastery of US surveillance and NDT devices

High temperature

- Na temperature during plant cold shutdown = 180℃
- Na temperature in operation = [425℃: 550℃]



→ Development and mastery of temperature proof ISI&R devices

Corrosion risk

- Under stress caustic corrosion in case of air ingress

Exo thermal reaction in case of leakage

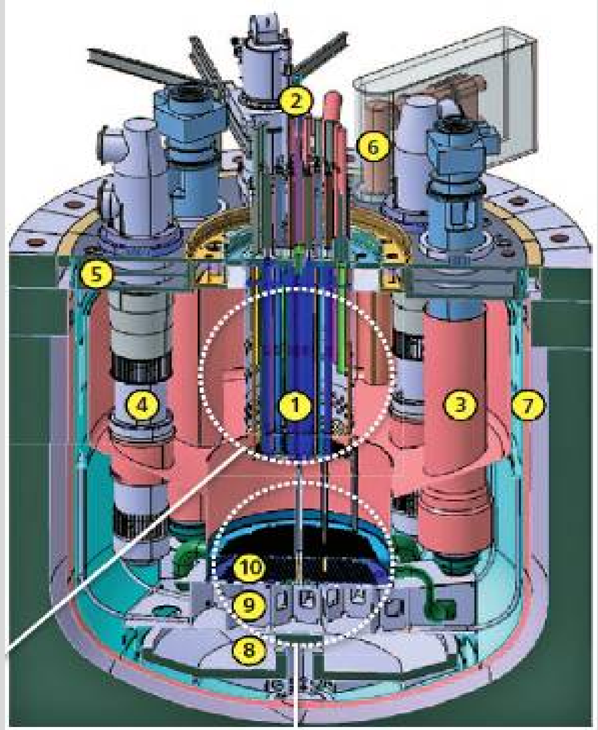
- Sodium fire when in presence of air *(containment leakage and T>120℃)*
- Sodium – water reaction *(SG leakage)*

→ Efficient surveillance means and mastery of the leaktight during the interventions

Main General Objectives for Examination and Inspection of SFRs

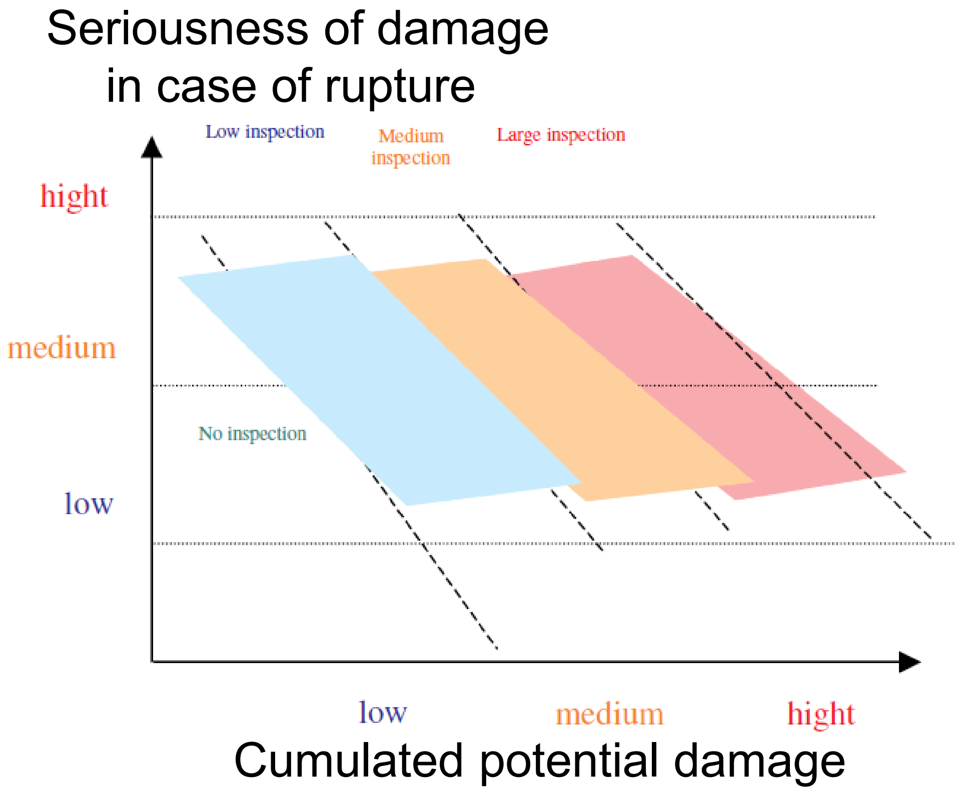
In Service Inspection refers to all the measures required to:

- Check that the operating conditions to which the structures are subjected are in line with the design assumptions.
- Guarantee that there will be no defects that are still incompatible with the safe operation of the facility.
- Enable the implementation of additional comprehensive examinations.

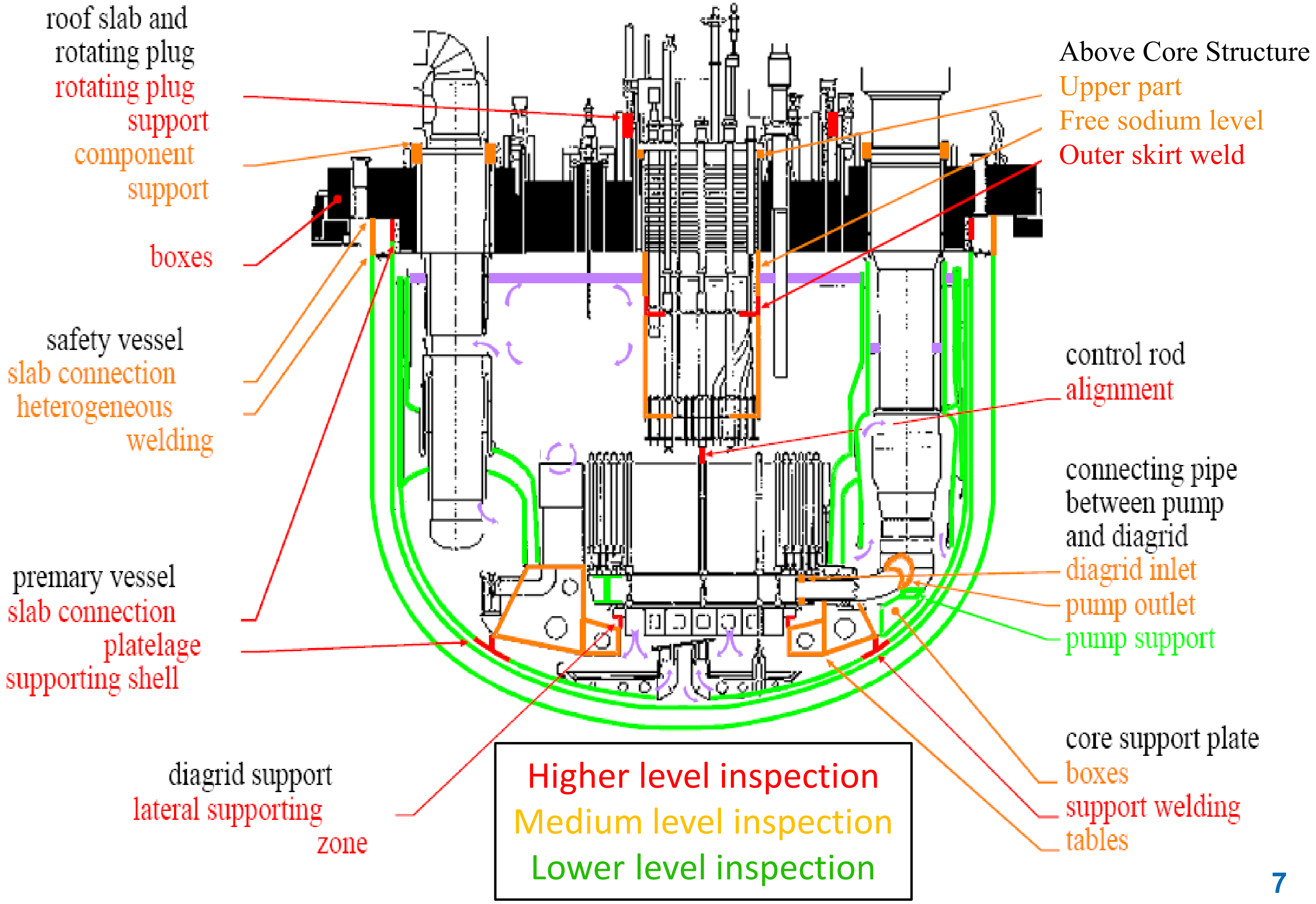


Large size
Many immersed components and structures in primary sodium Vessel

Risk Informed Method Application for SFRs

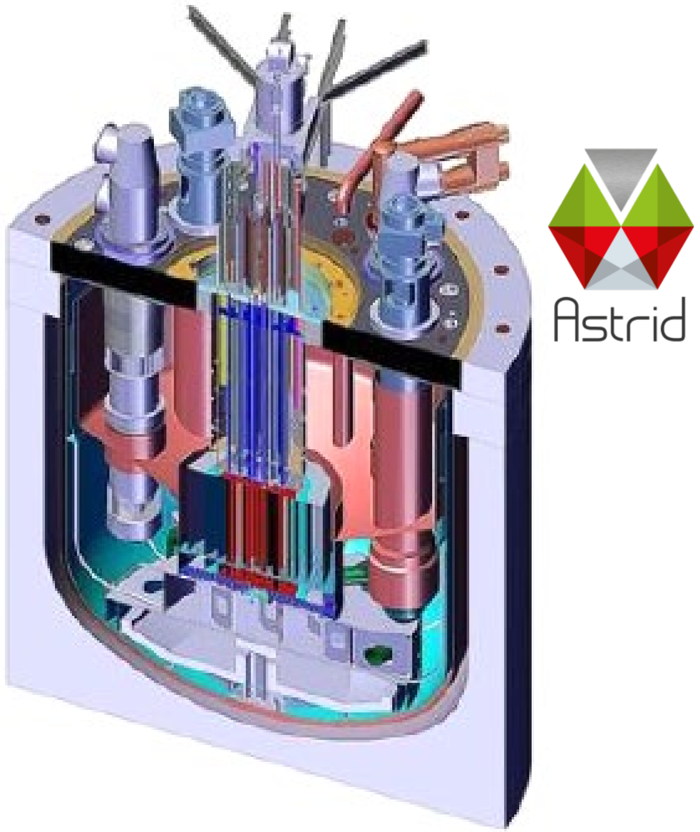


Example for Superphenix reactor block inspection



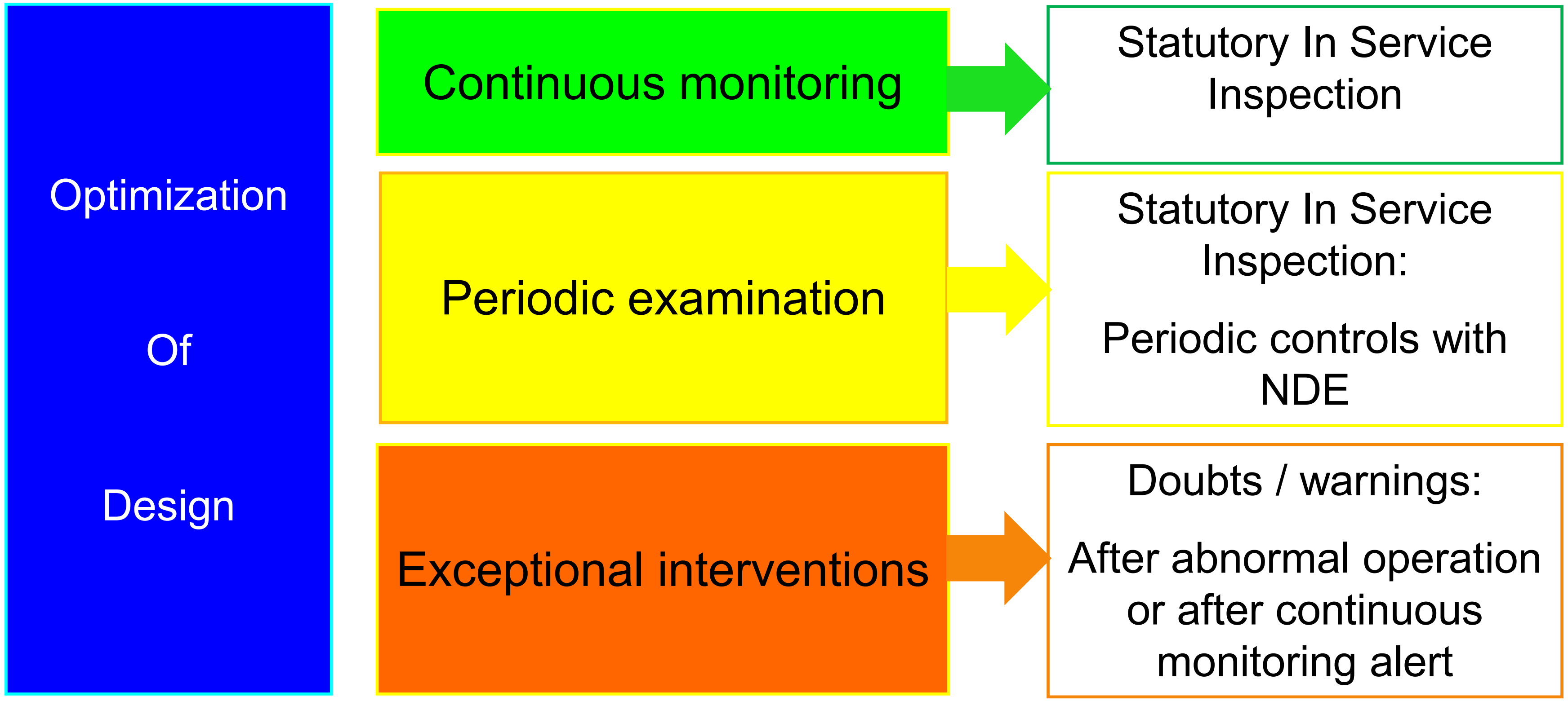
Main Concrete Objectives for Examination and Inspection of SFRs

- **Minimizing the surveillance, examination and repair needs**
  - **By potential damage risk reduction**
    - Robust design proposal
    - Reduction of the weak areas
- **Make possible every kind of examinations**
  - **Access improvements**
    - Sufficient accessibility
    - Suitable positioning of areas to be inspected
  - **Examination ability improvements**
    - Design dedicated to NDT performing
  - **Possibility for exceptional provisions**
    - Whole Core Discharge (WCD)
    - Na draining

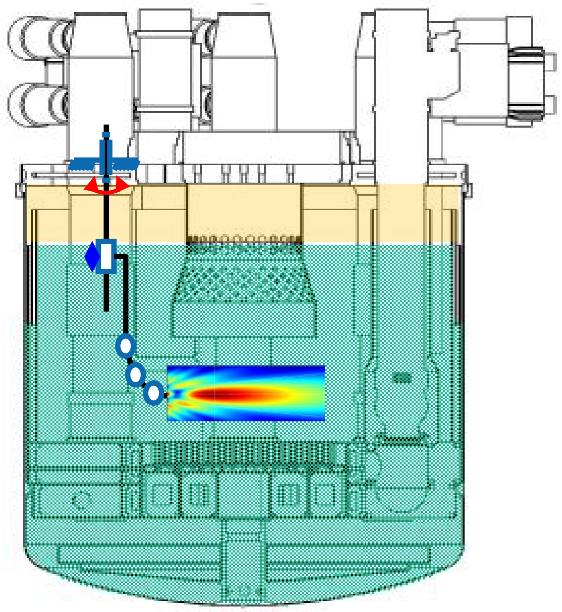


- **Solve a failure case**
  - **Repair ability thanks to a simple design**
  - **Replacement ability thanks to dedicated dismountable junctions**

French R&D Program for Non Destructive Examination and In Service Inspection of SFRs



Developments of Examination and Inspection Techniques for SFRs



Inspection mainly with ultrasonic means:

- Liquid sodium is opaque, not easy to drain.
- Ultrasonic metrology chosen as key technology to render feedback for in sodium inspection: *Propagation, Damping, Reflection and Diffraction of Ultrasonic Waves*

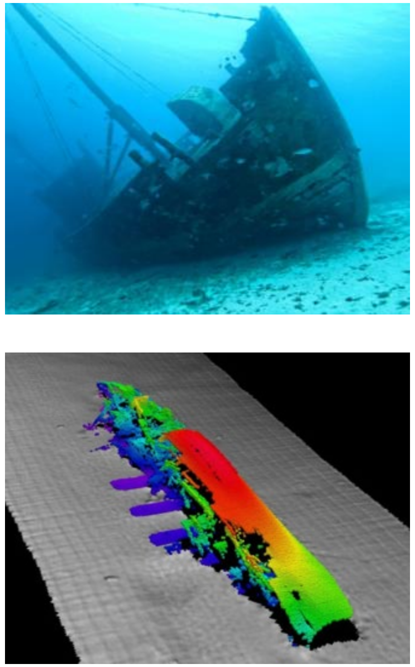
Acoustic techniques:
- Low attenuation by the sodium medium
- High velocity of US wave (≈ 2400 $m.s^{-1}$ at 200°C)

French R&D Program for ASTRID Non Destructive Examination:

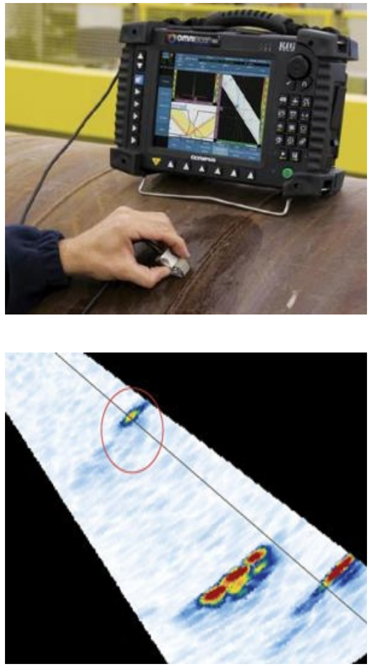
- *Telemetry* of specific targets in the reactor block
- *Imaging* of local and general areas, of lost parts, of opened cracks, identification of fuel elements, positionning for robotics
- *Volumetric control* of immersed structure welded joints

Developments of Examination and Inspection Techniques for SFRs

A solution for scanning :
Ultrasonics



Sonar



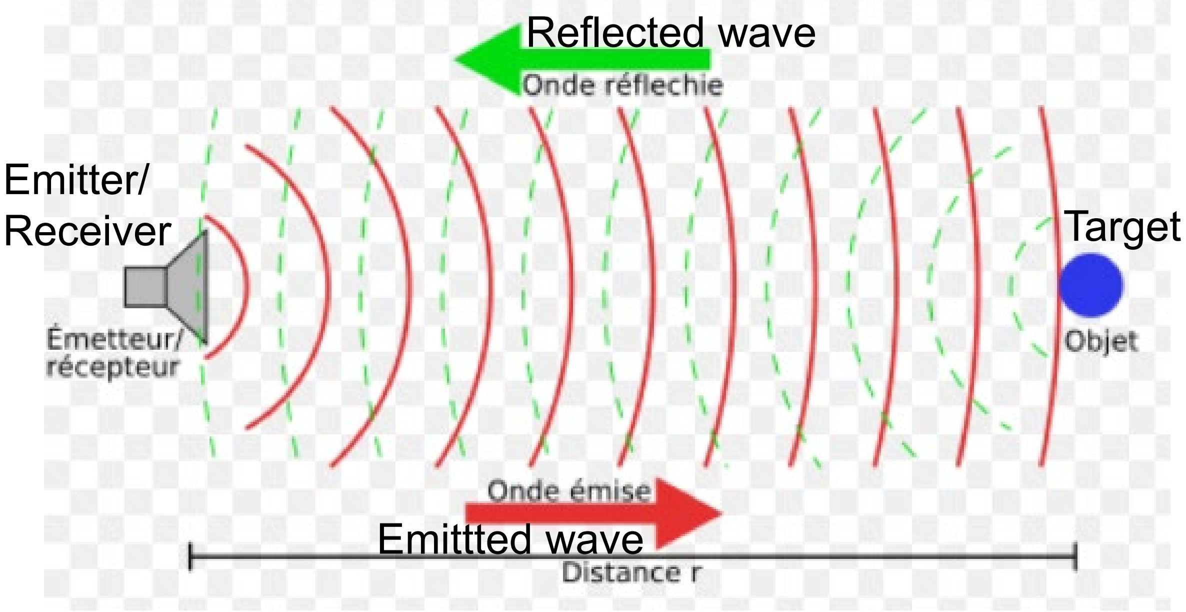
Non
Destructive
Examination

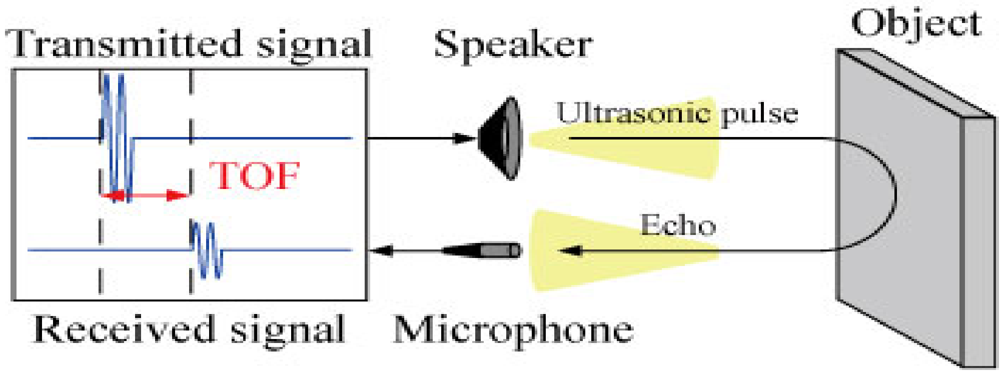
Medicine

GEN IV International Forum
Expertise | Collaboration | Excellence

Developments of Examination and Inspection Techniques for SFRs

Principle for ultrasonic measurement





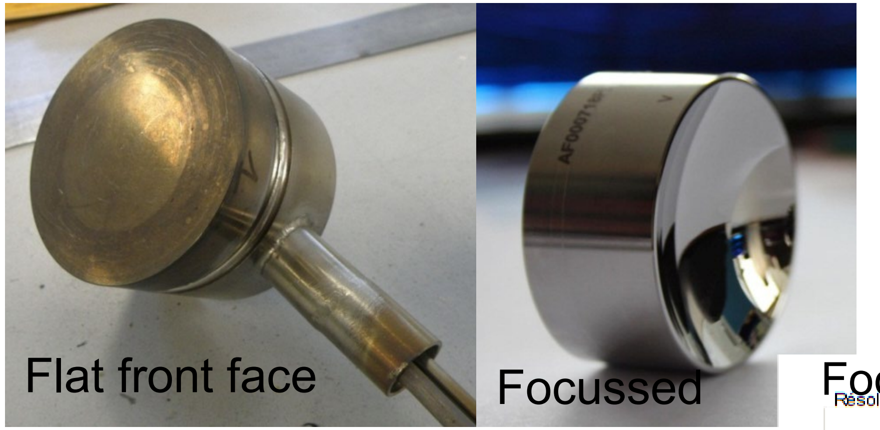
Distance =

Wave speed in the media (m/s)
x
Time of flight (s)
/ 2
(outward & return)

Sensors: Under Sodium Ultrasonic Transducers

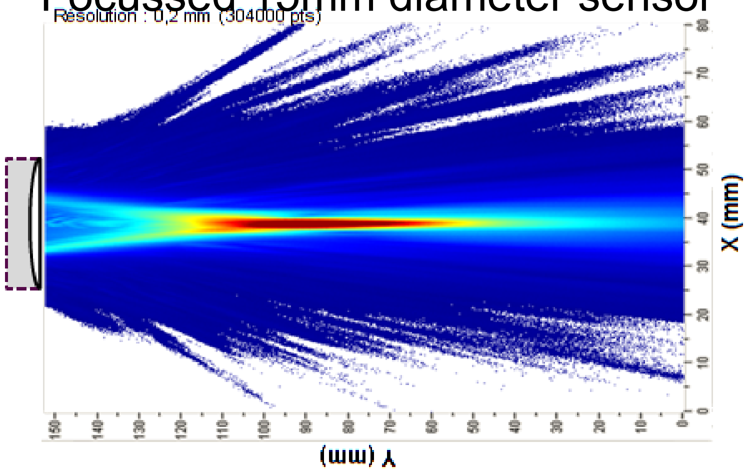
TUSHT^{CEA} sensors

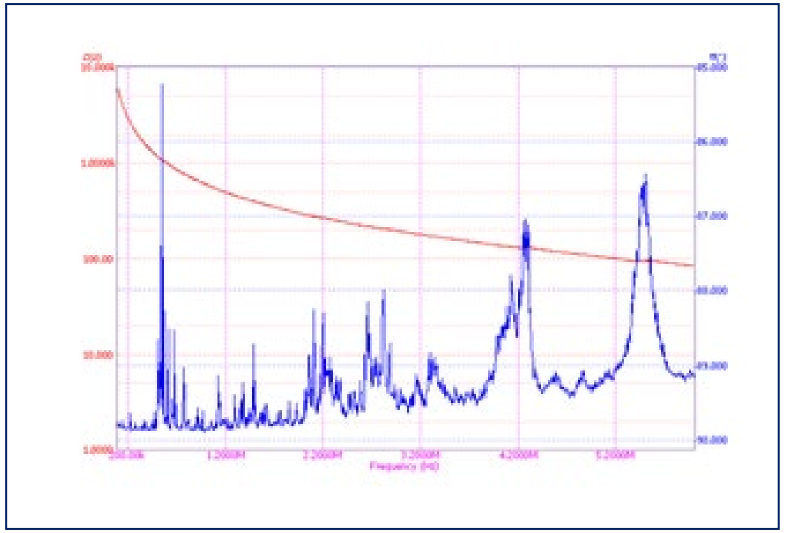
- ✓ Accurate qualification in water: flat front face, 15 to 40mm diameter
- ✓ Acoustic beam field
- ✓ 5 main frequencies (0.7 – 4.5MHz)



- ✓ Wetting of front face in liquid sodium:
  - ✓ With coating on stainless steel
  - ✓ In some hours above 350°C

Focussed 15mm diameter sensor





GEN IV International Forum
Expertise | Collaboration | Excellence

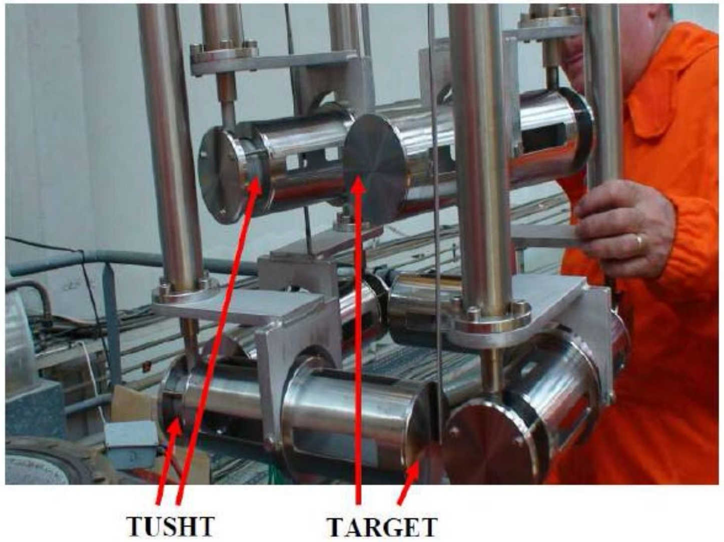
Sensors: Under Sodium Ultrasonic Transducers

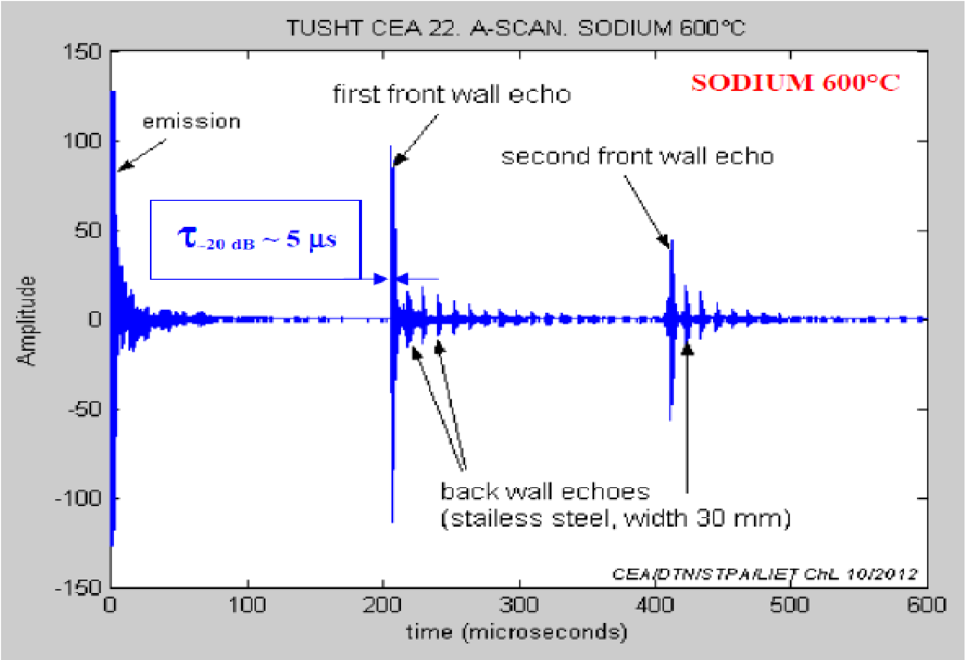
TUSHT^{CEA} sensors

Qualified in sodium

in the range 200°C - 600°C

constant sensitivity t_{-20dB} ~ 5 ms





Sensors: Under Sodium Ultrasonic Transducers

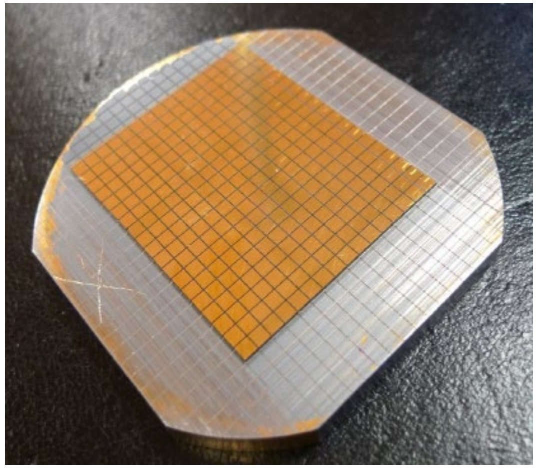
TUSHT[CEA] sensors … Coming to phased array…

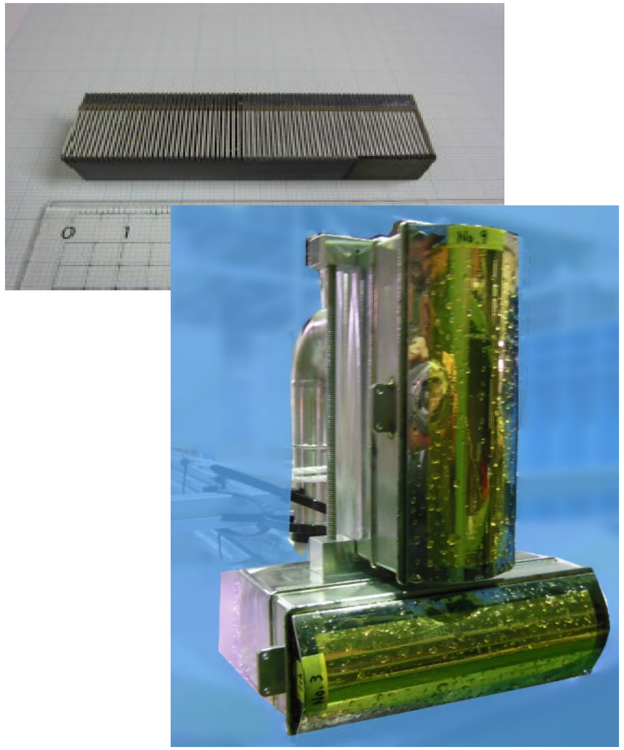
SONAXIS

2013 - 2019

TOSHIBA

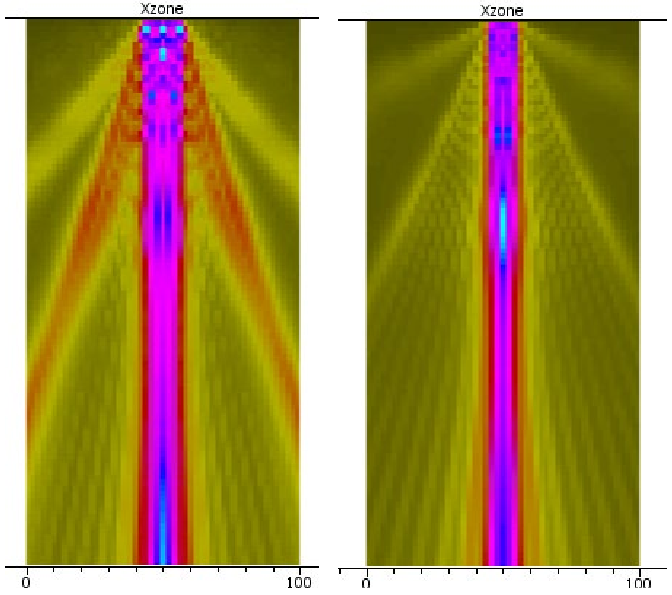
2014 – 2019





CIVA NDE 11

CIVA software simulation for optimization

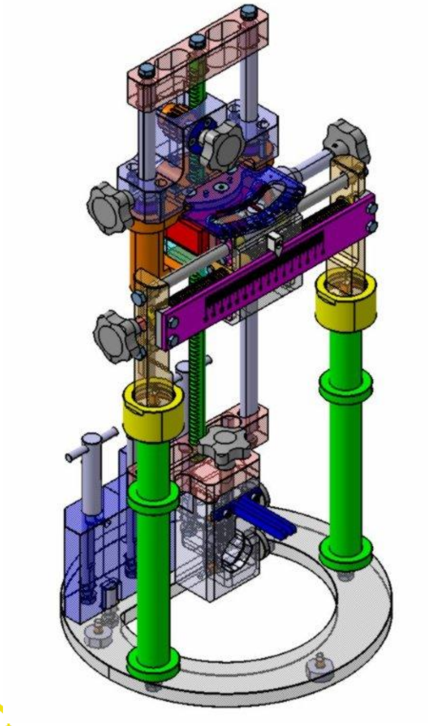


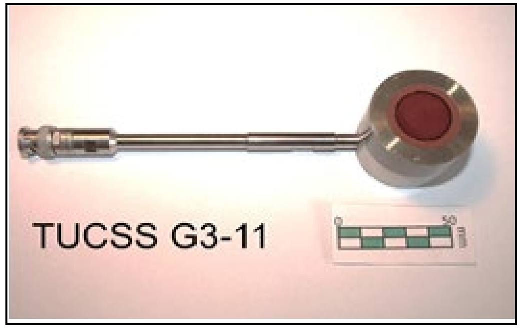
Sensors: Under Sodium Ultrasonic Transducers

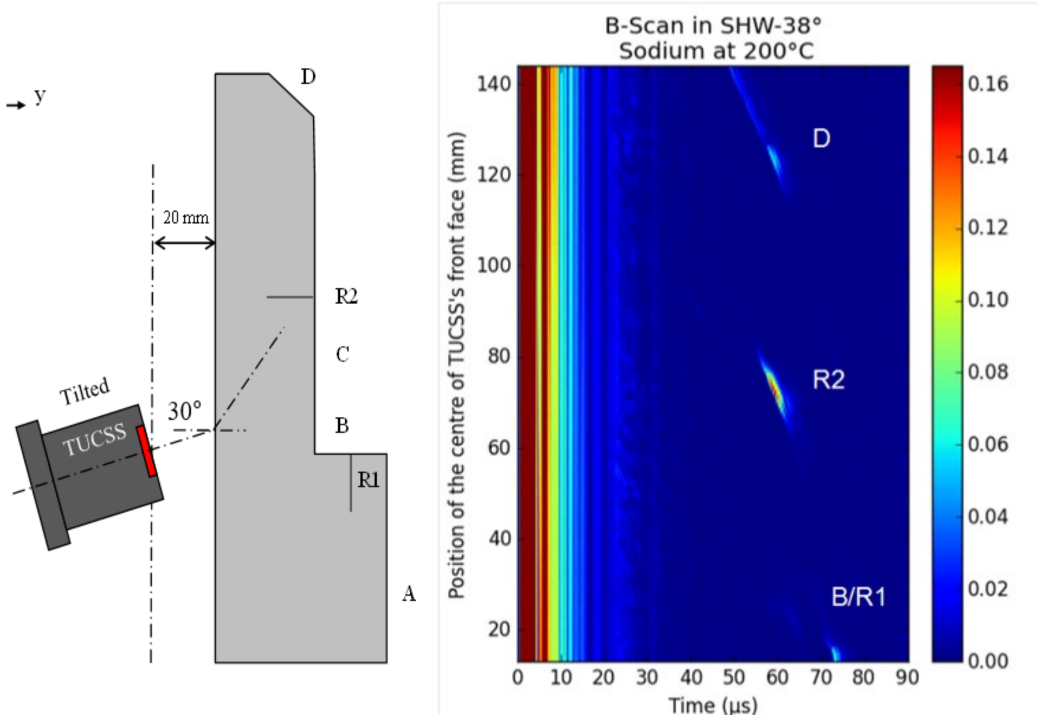
TUCSS^{FRAMATOME} sensors

Qualified in water then in sodium at 200°C

20mm diameter, 2MHz, polished or polymer front face



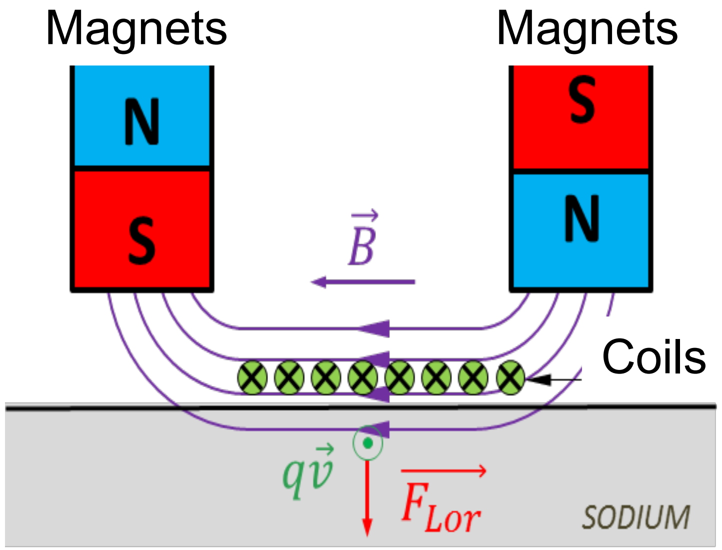




GEN IV International Forum
Expertise | Collaboration | Excellence

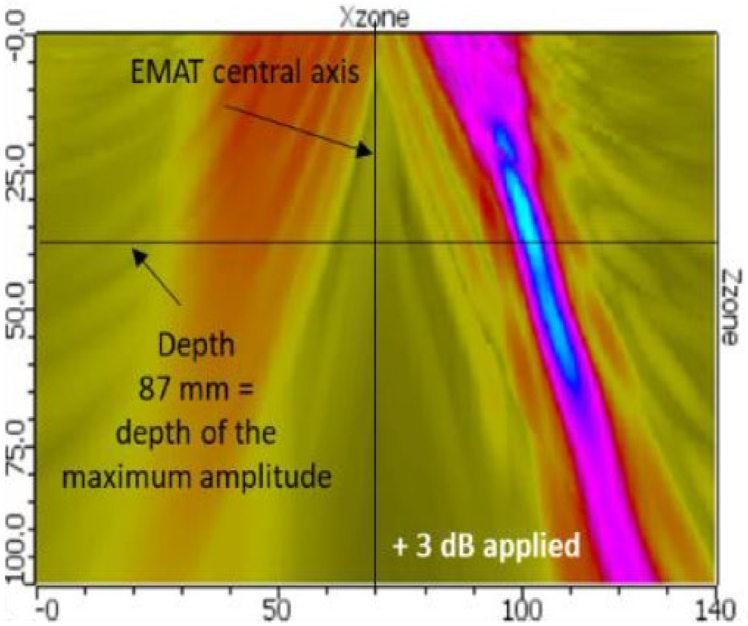
Sensors: Under Sodium Ultrasonic Transducers

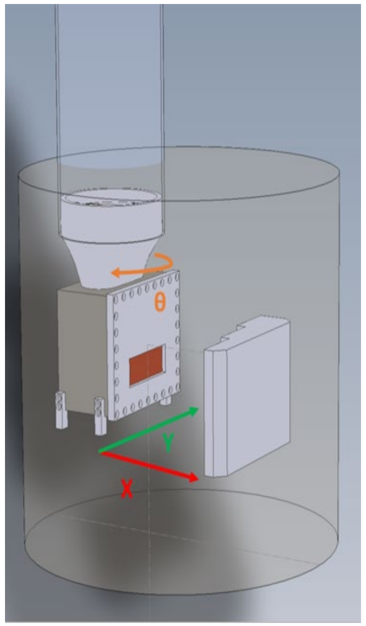
EMAT sensors

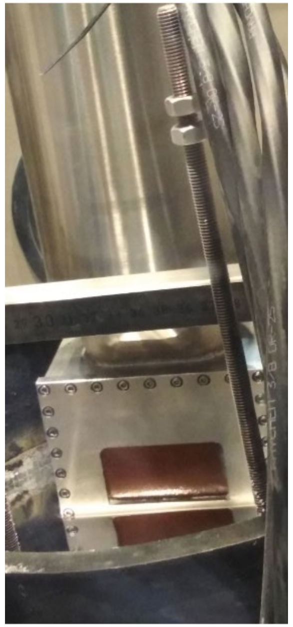


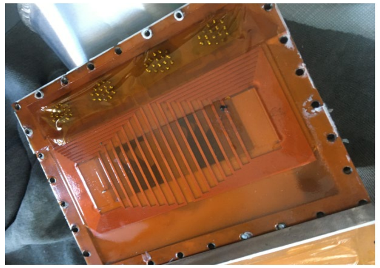
Overcoming wetting problem as pressure waves are directly generated inside coolant

Development of an Optimized 12-Element Phased Array EMAT









Sodium tests at 180°C :

- Ability to steer and focus the ultrasonic beam to the desired focal spots using electronic delay laws
- Ability for telemetry, vision, Non Destructive Examination

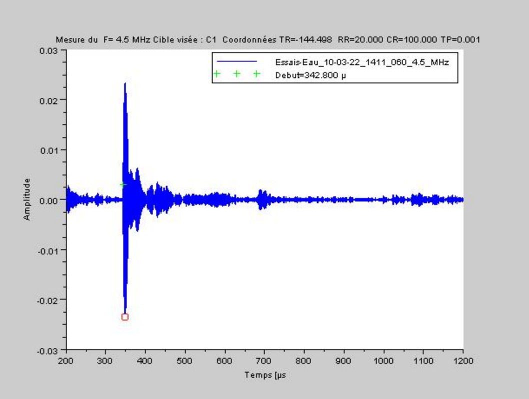
GEN IV International Forum
Expertise | Collaboration | Excellence

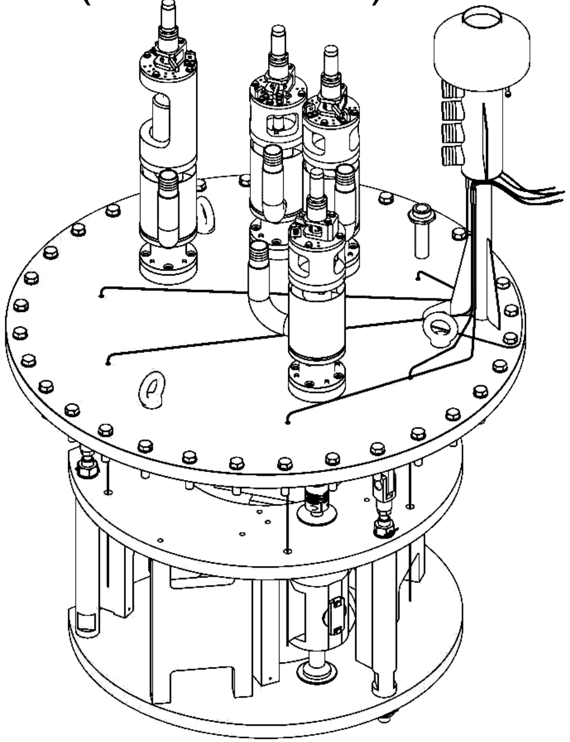
Under Sodium Telemetry

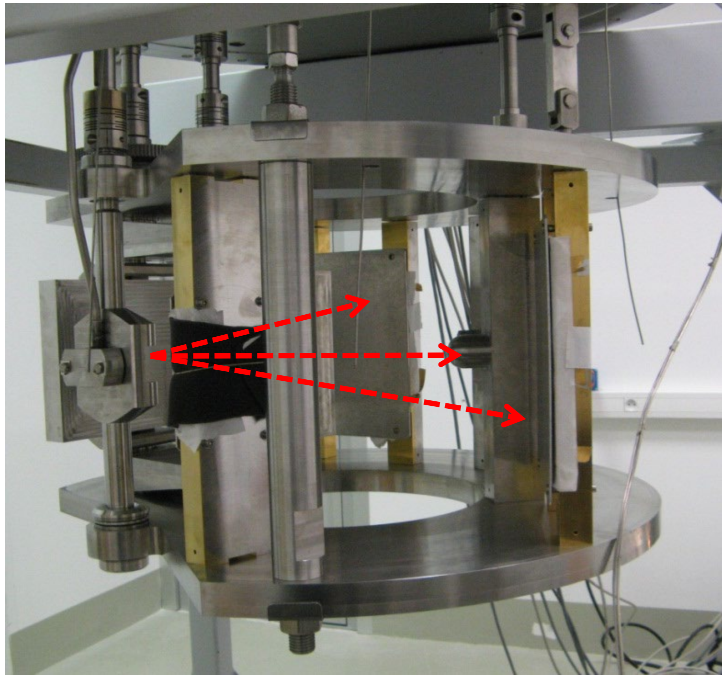
MULTIREFLECTOR tests

- 40mm diameter TUSHT^{CEA} (flat front face)
- 6 targets (SS 316L)

  Position accuracy:
  ± 0.02 mm (20µm)
  ± 0.02°
- 1m diameter vessel







Sodium tests at 200°C :
- ✓ ultrasonic distance measurement was proved to be better than 100 µm
- ✓ The test results helped qualify the CIVA code.

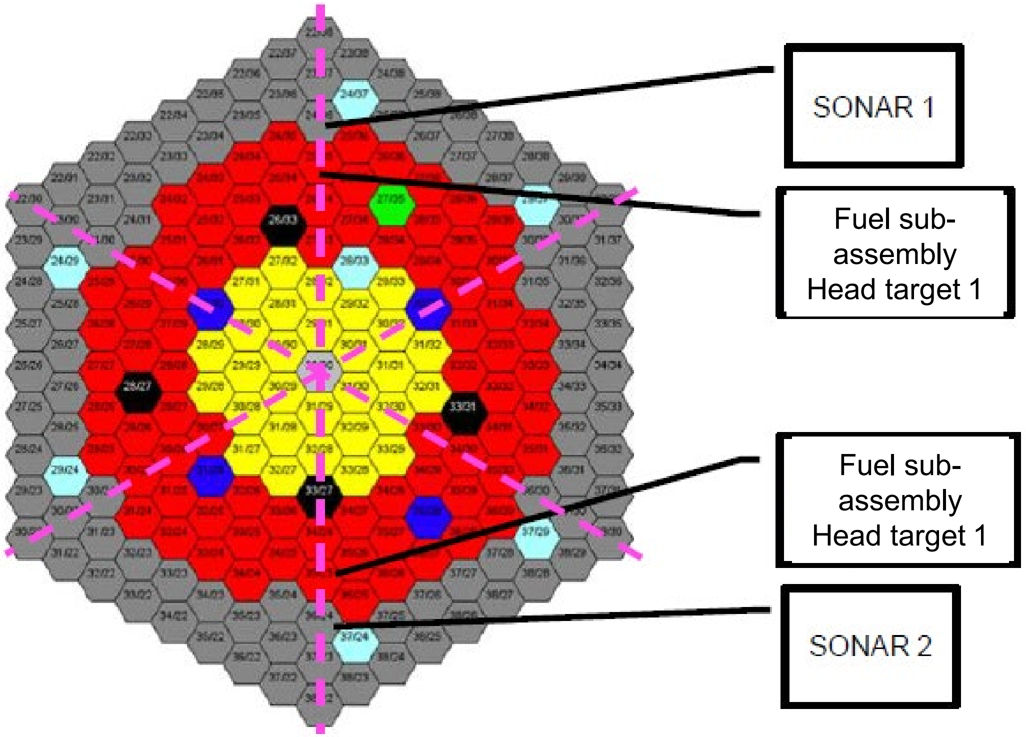
Under Sodium Telemetry

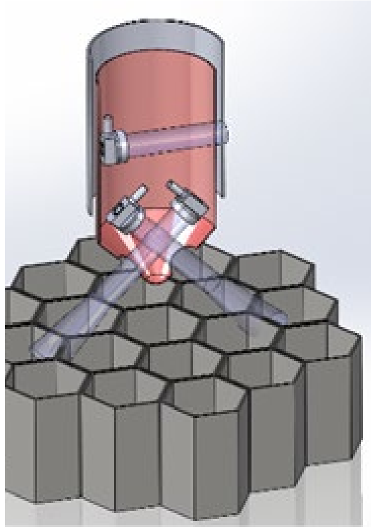
In sodium SONAR device

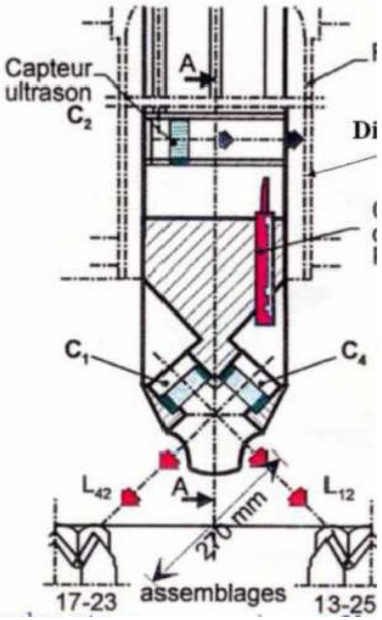
For checking

2 fuel sub-assembly head movements

At Phénix Plant, from 1996 to 2009



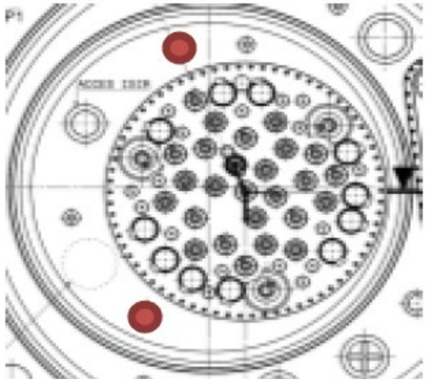




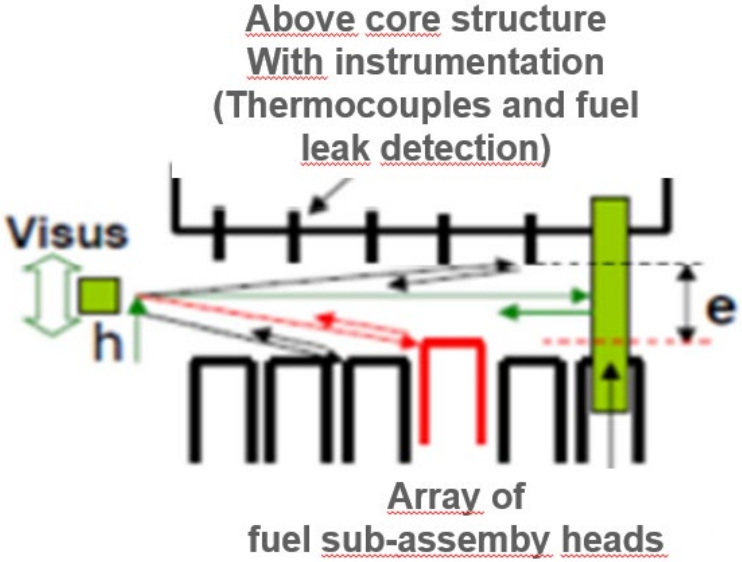
Under Sodium Telemetry

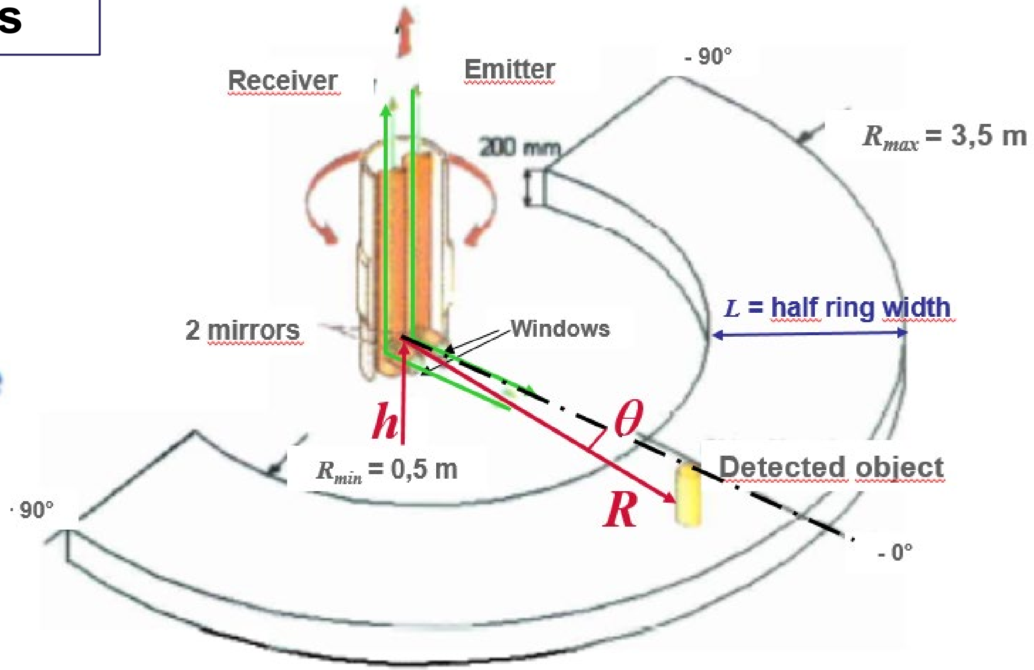
For obstacle detection in sodium, at core outlet

Principle: no ultrasonic echo from any physical obstacle which could be located between core outlet and control plug



Phénix Plant VISUS Design and ranges

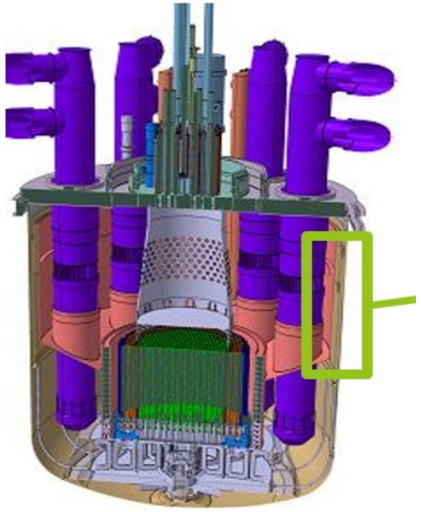


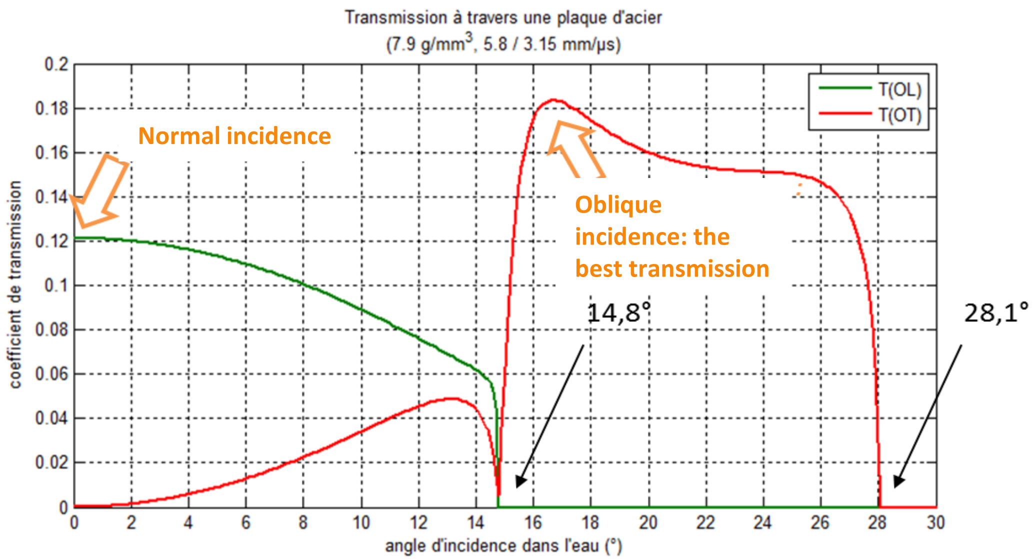


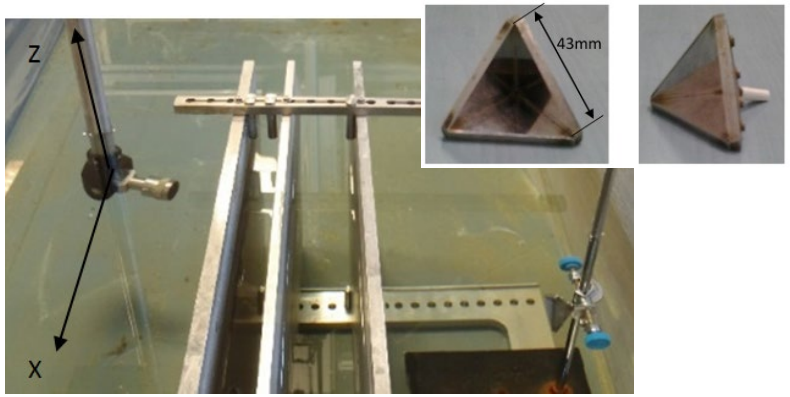
Under Sodium Telemetry

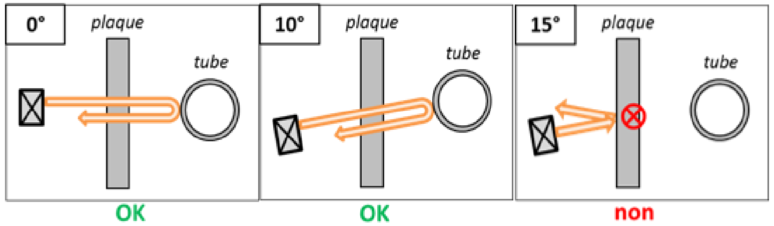
Ultrasonic mesurement through screen/wall

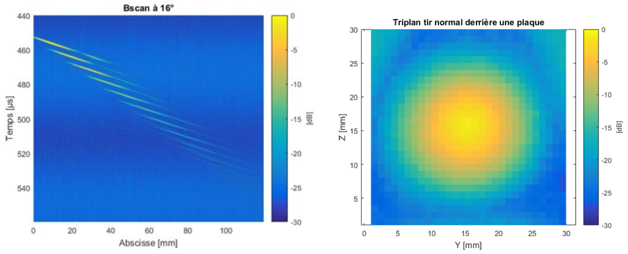
Acoustic waves to come from sensor to target, then back











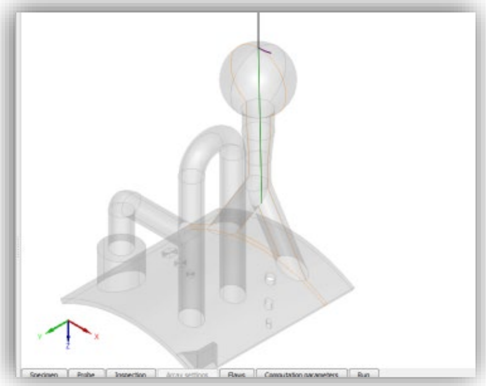
GEN IV International Forum
Expertise | Collaboration | Excellence

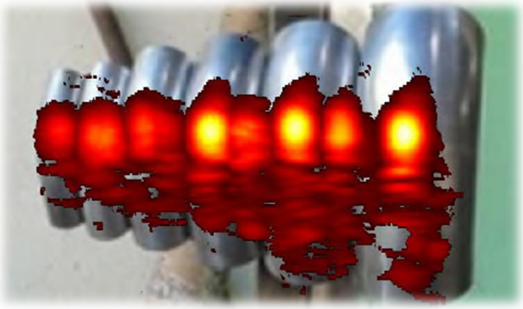
Under Sodium Near Distance Imaging

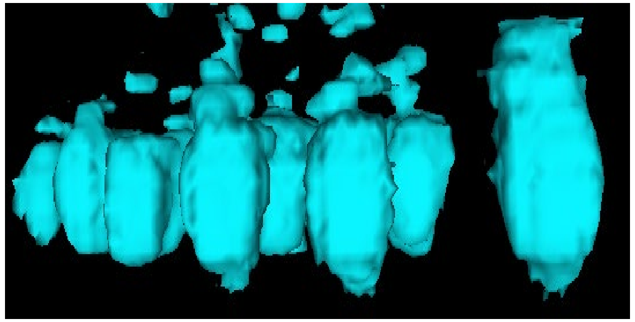
Ultrasonic vision at less than 20 cm

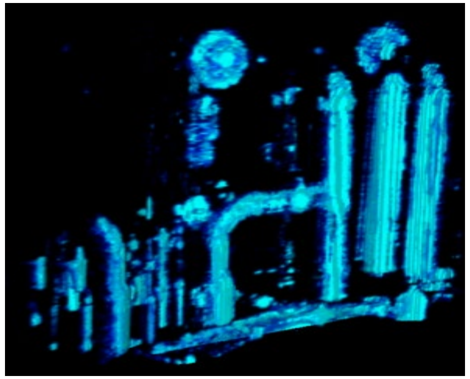
Definition of a whole ‘sodium-proof movie camera’ system:

- ✓ Ultrasonic sensors (with electronics)
- ✓ Methods for wave emission, for optimal scanning
- ✓ Technics for image reconstruction (B-Scan, C-Scan)
- ✓ Simulation: CIVA software platform





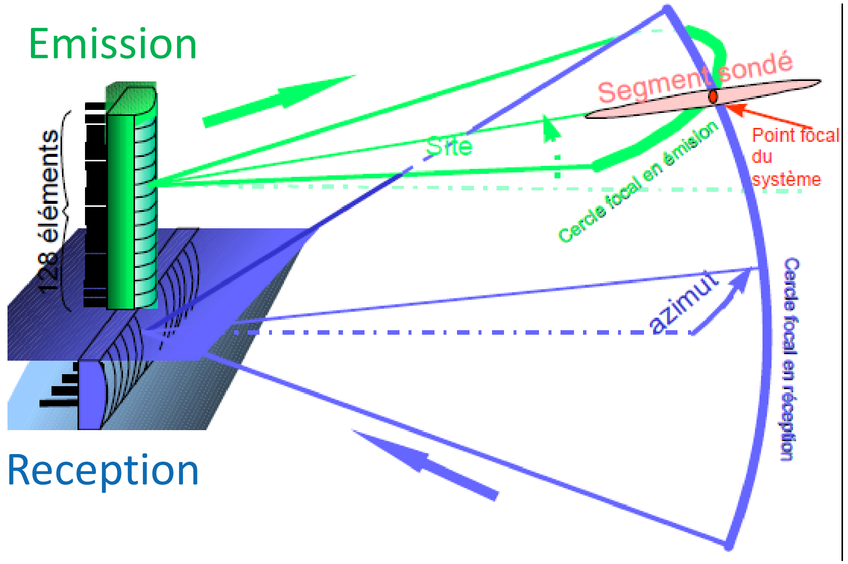




GEN IV International Forum
Expertise | Collaboration | Excellence

Under Sodium Near Distance Imaging

Ultrasonic vision at less than 20 cm



Associated parameters:

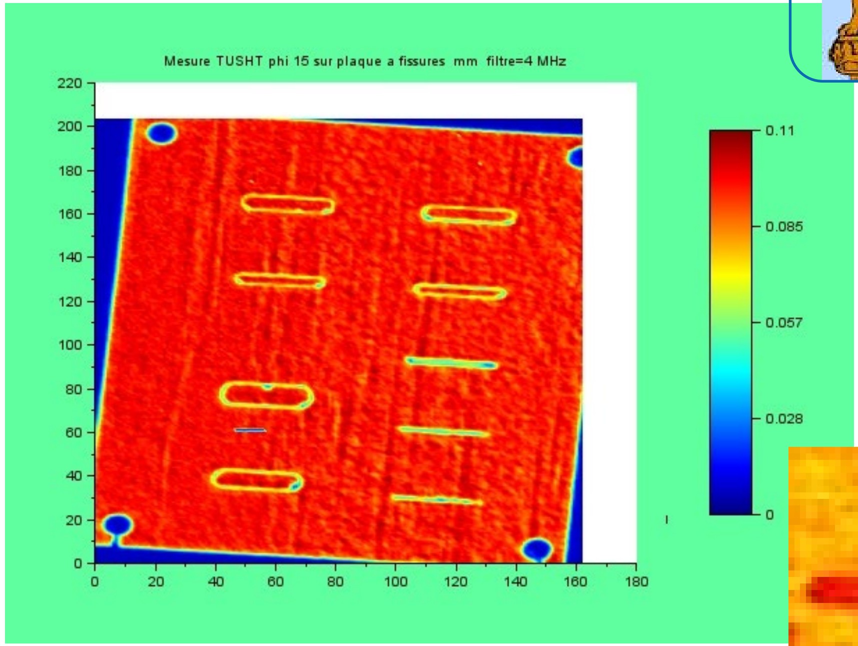
- ✓ Solid angle of imaged area: electronic sweeping with phased array, or single element with robot
- ✓ Lateral resolutions (site and azimuth)
- ✓ Axial resolution (in depth)
- ✓ Time for image reconstruction… in real time?
- ✓ Time for automatic analysis… on line ?
- ✓ Options for 2D/3D imaging
- ✓ Signal to noise ratio

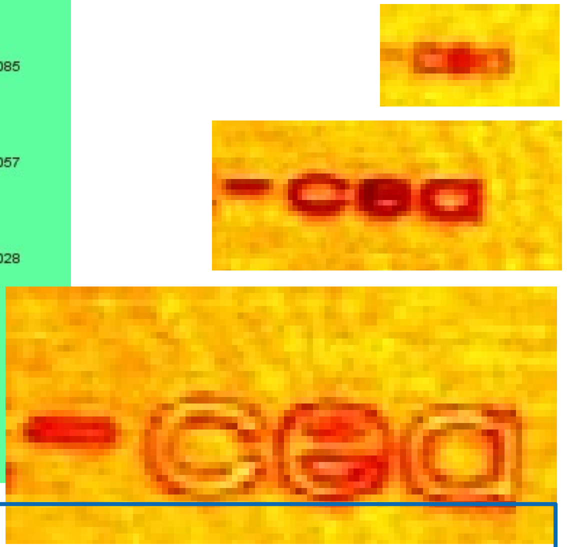
Under Sodium Near Distance Imaging

SCK•CEN
2012 - 2016

IGCAR
2011 - 2016

Surface metrology: engraved letters and slits





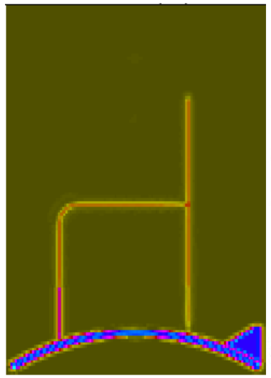
Water tests (echoes amplitude):

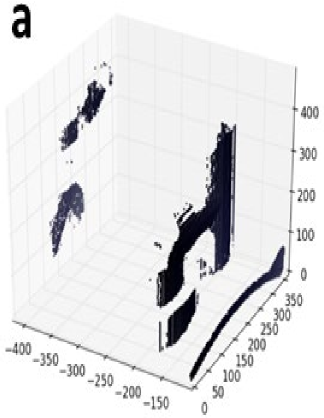
- ✓ Detection up to 800 µm slit (idem optical)→ Detection of possible cracks
- ✓ More than 6mm letters are readable with TUSHT[CEA]

GEN IV International Forum
Expertise | Collaboration | Excellence

Under Sodium Near Distance Imaging

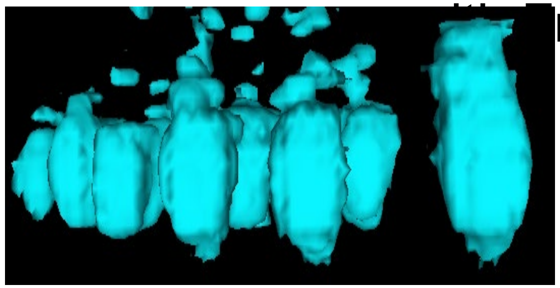
Qualification of imaging
in water tests
with TUSHT^{CEA}

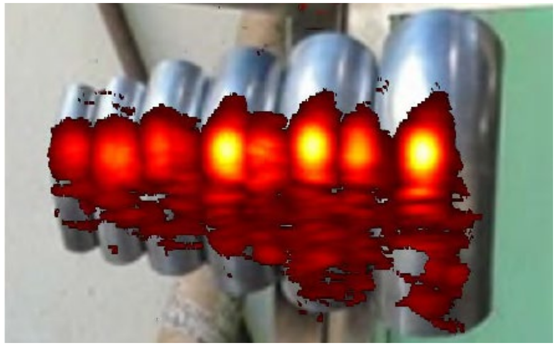


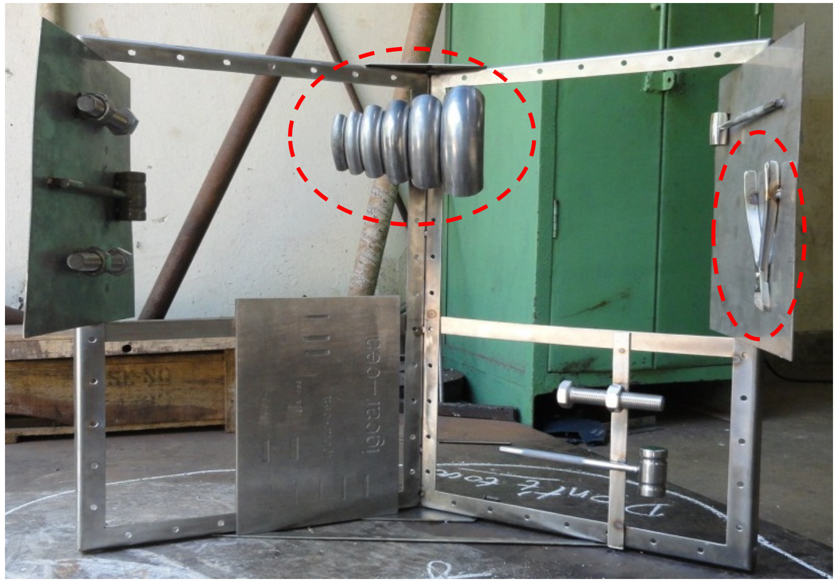


Qualification of imaging: first in sodium tests at IGCAR (2013)

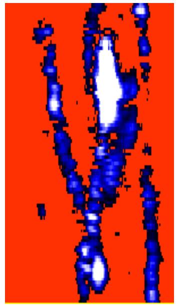
rench TUSHT^{CEA} at 400°C

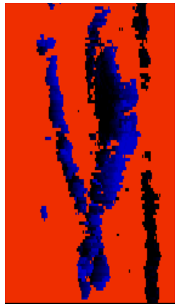






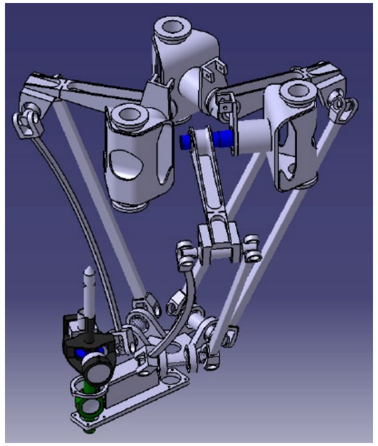
IGCAR
2011 - 2016

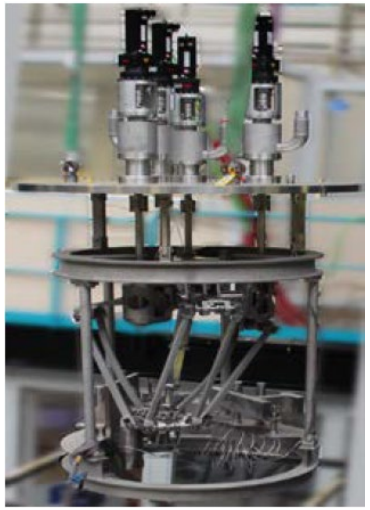




GEN IV International Forum
Expertise | Collaboration | Excellence

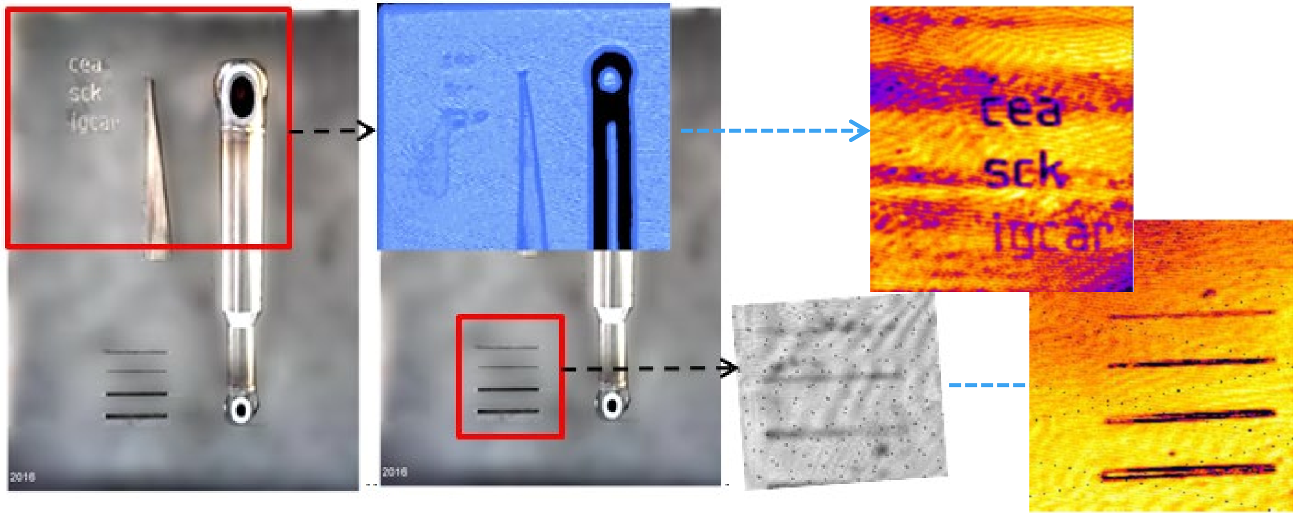
Under Sodium Near Distance Imaging

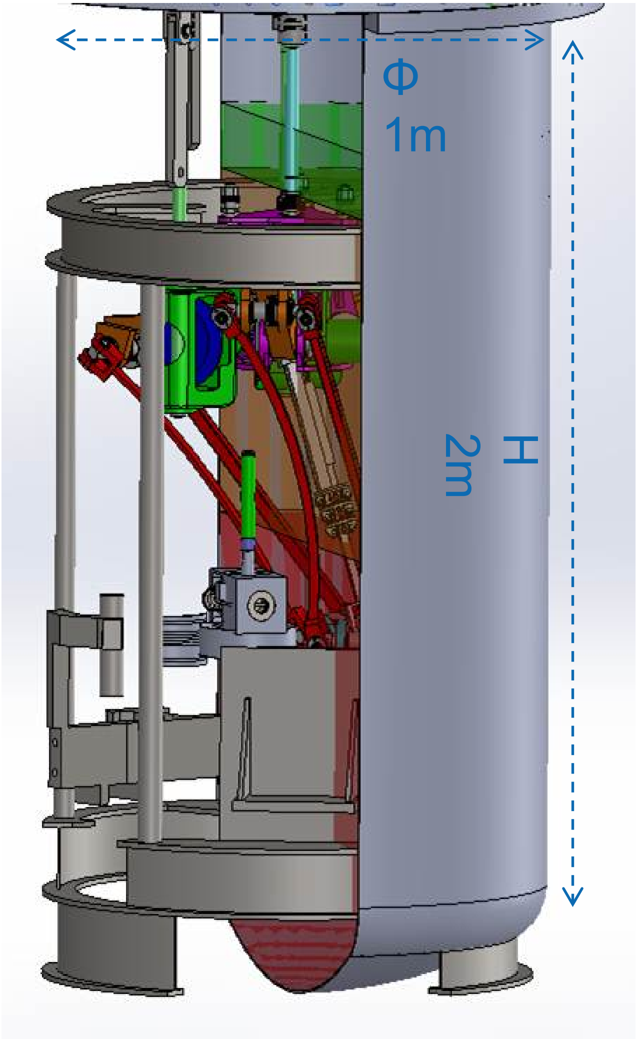




Qualification in 200°C sodium with VENUS facility at 200°C:

- ➢ With 3D robot
- ➢ With TUSHT[CEA] sensor (flat and focused front face)



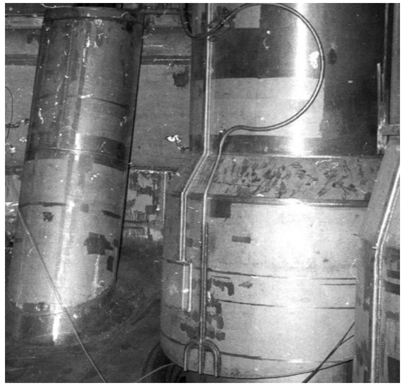


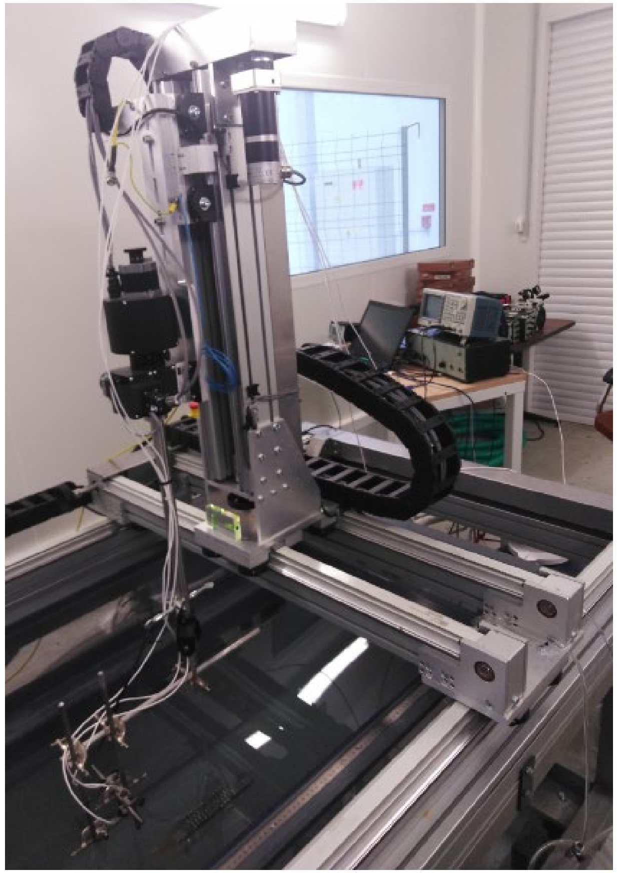
Under Sodium Longer Distance Imaging

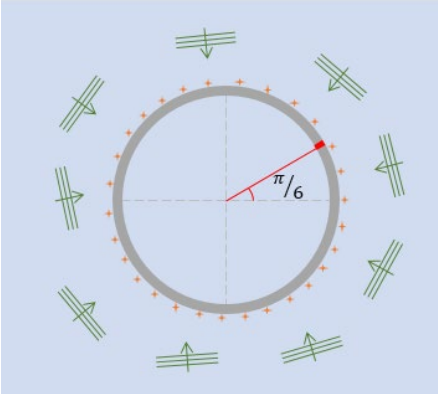
Ultrasonic vision at more than 20 cm

Using sub-marine acoustic techniques

Taking benefit of ambiant noise (only recording)

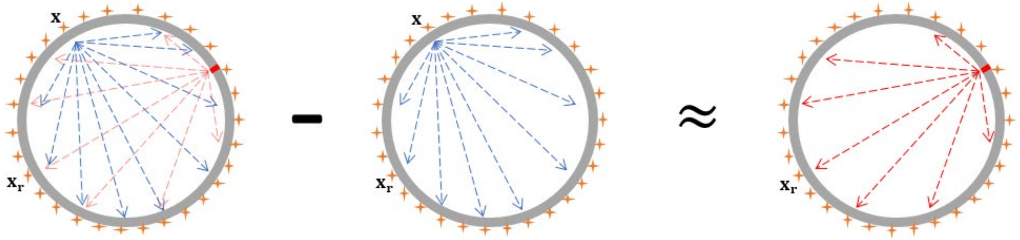


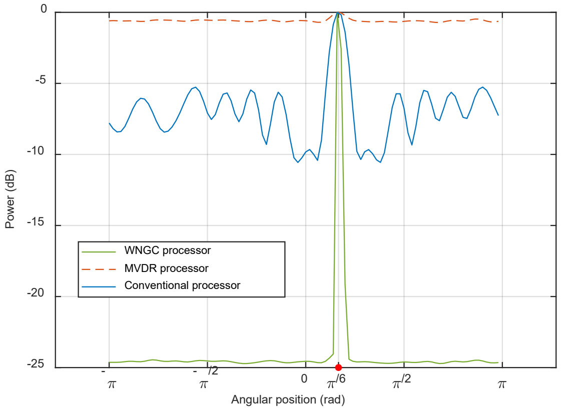




Structure to be controlled (1 local defect)

Structure in reference state (with no defect)



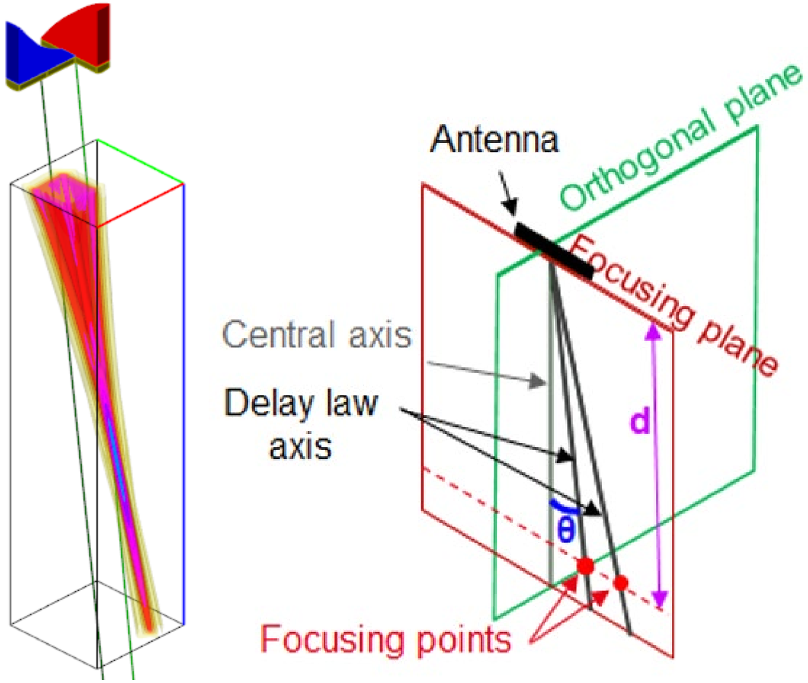


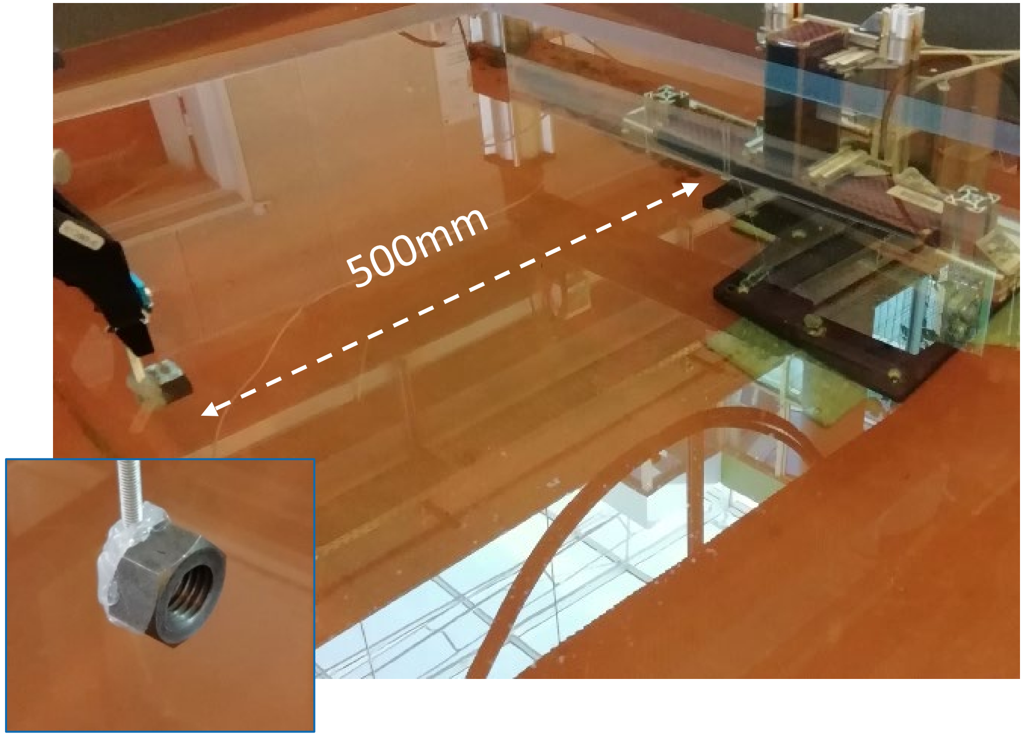
GEN IV International Forum
Expertise | Collaboration | Excellence

Under Sodium Longer Distance Imaging

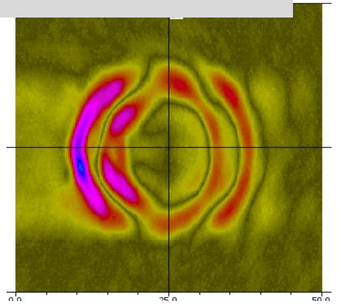
Ultrasonic vision at more than 20 cm

Concept with 2 orthogonal antennas (with phased arrays)

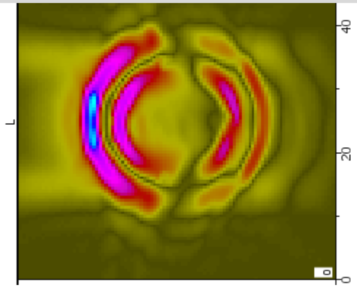




Acoustic measurement



CIVA sofware simulation



3D scanning = intersection of 2 antennas focal points

Changing delay laws of each phased array (each antenna), focussing point (distance + angle) changes.

Under Sodium Imaging for Non Destructive Examination

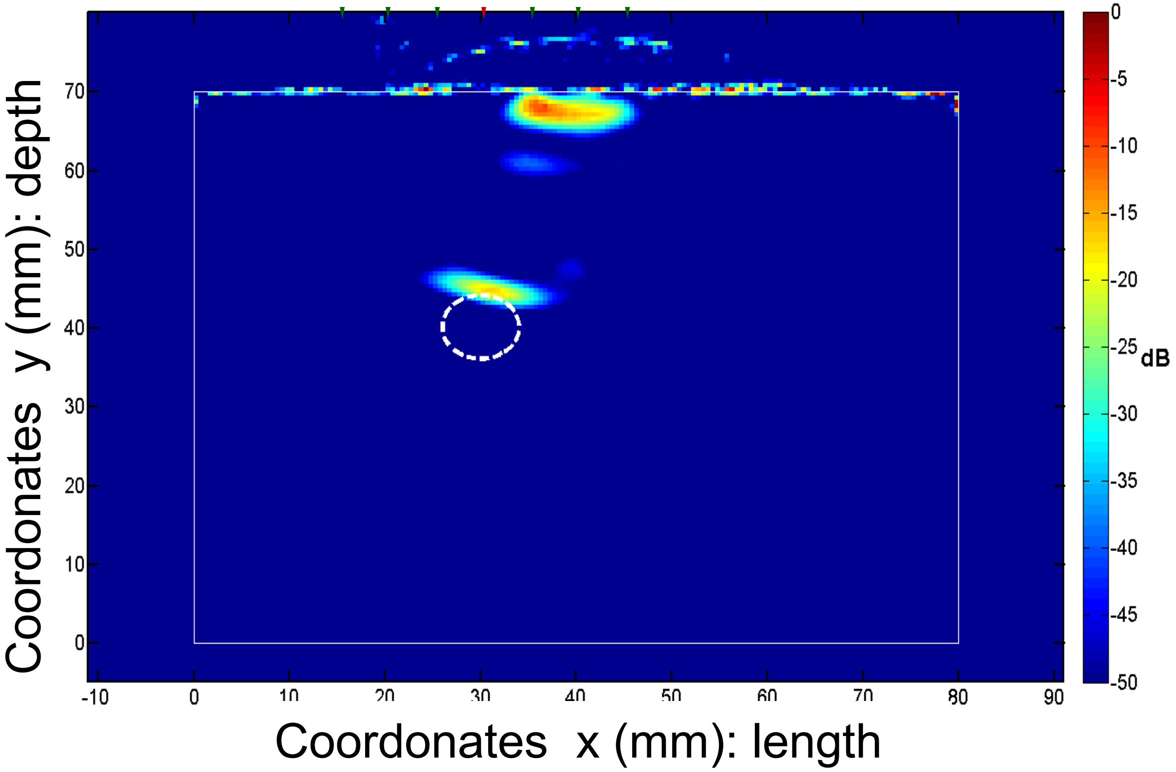
Heterogeneous medium: differential method

A 3 step-process:

1. Extracting acoustic field due to the perturbation. This step consists in making the difference between a reference medium and the inspected one.
2. Focusing on defect location using time-reversal techniques.
3. Imaging while computing the time-gated topological energy.

Aix*Marseille université
2014 - 2016

Topological energy mapping



$$ET(x) = \int_{\frac{d(x)}{c}-\frac{\Delta t}{2}}^{\frac{d(x)}{c}+\frac{\Delta t}{2}} \|u_0(\boldsymbol{x},t)\|^2 \|v_{rt}(\boldsymbol{x},T-t)\|^2 dt$$

GEN IV International Forum
Expertise | Collaboration | Excellence

Under Sodium Imaging for Non Destructive Examination

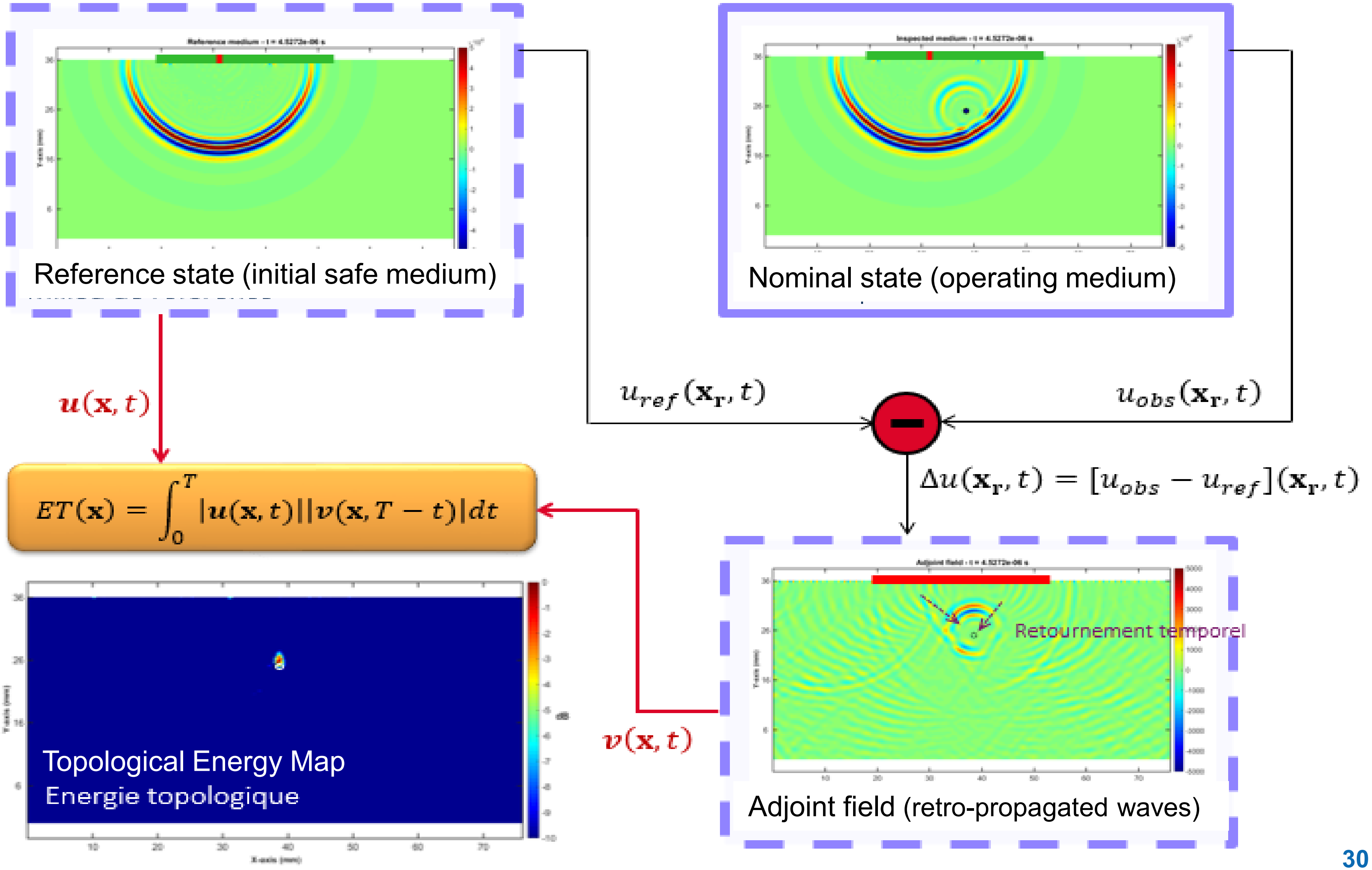
Aix*Marseille université

2014 - 2016

Topogical

Energy

Method

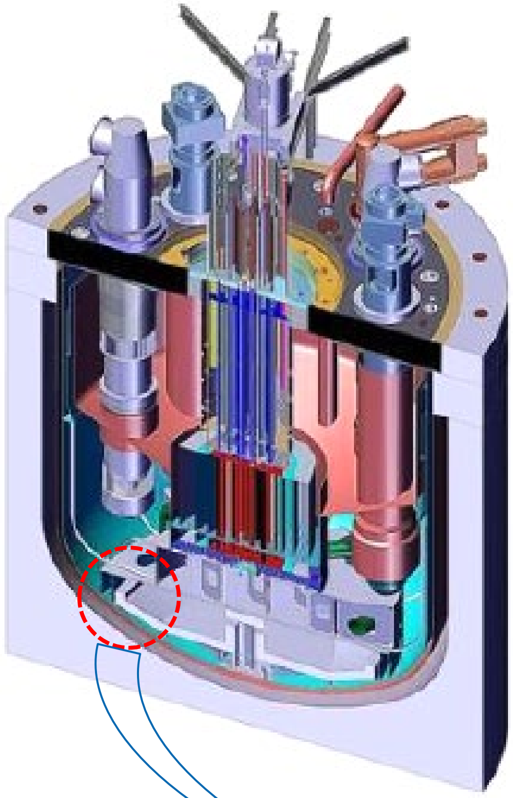


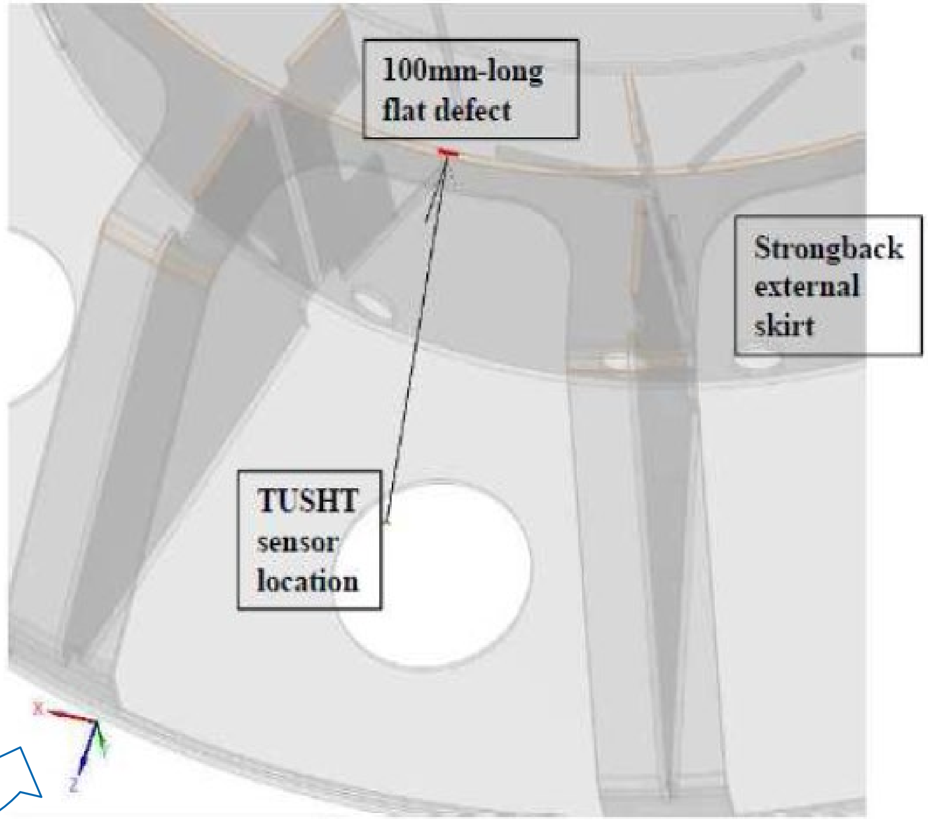
GEN IV International Forum

Expertise | Collaboration | Excellence

Under Sodium Non Destructive Examination of Welded Joints

within the ASTRID Supporting Core Structure (so called strongback) using TUSHT^{CEA} ultrasonic transducer in liquid sodium

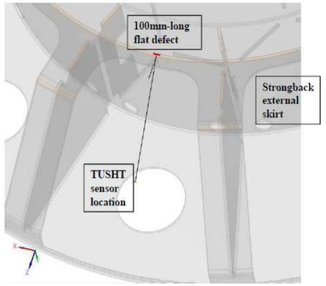




GEN IV International Forum
Expertise | Collaboration | Excellence

Under Sodium Non Destructive Examination of Welded Joints

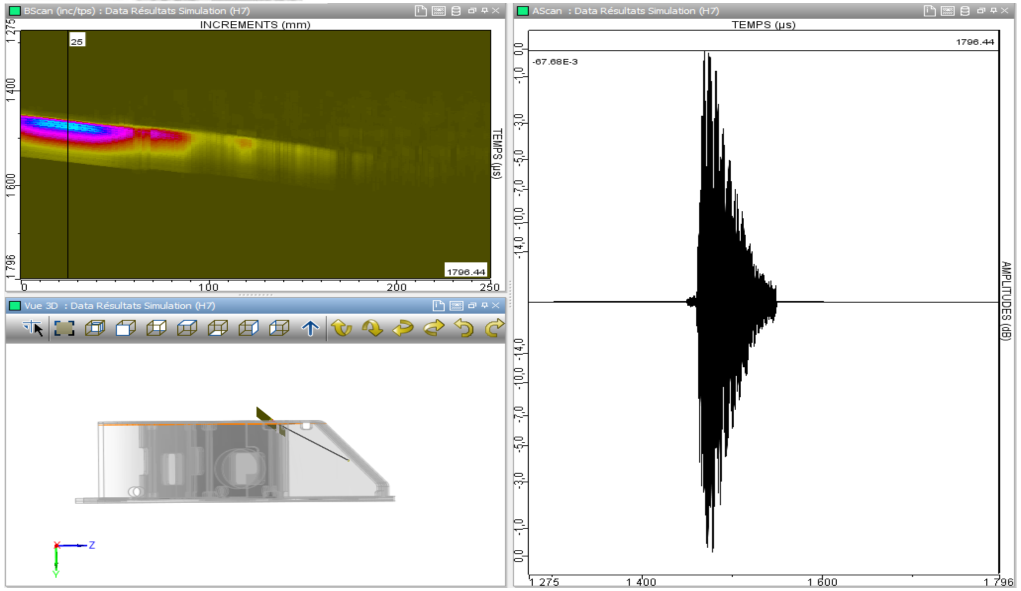
within the ASTRID Supporting Core Structure (so called strongback)

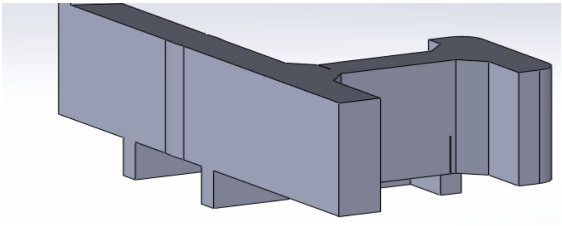


CIVA software simulation

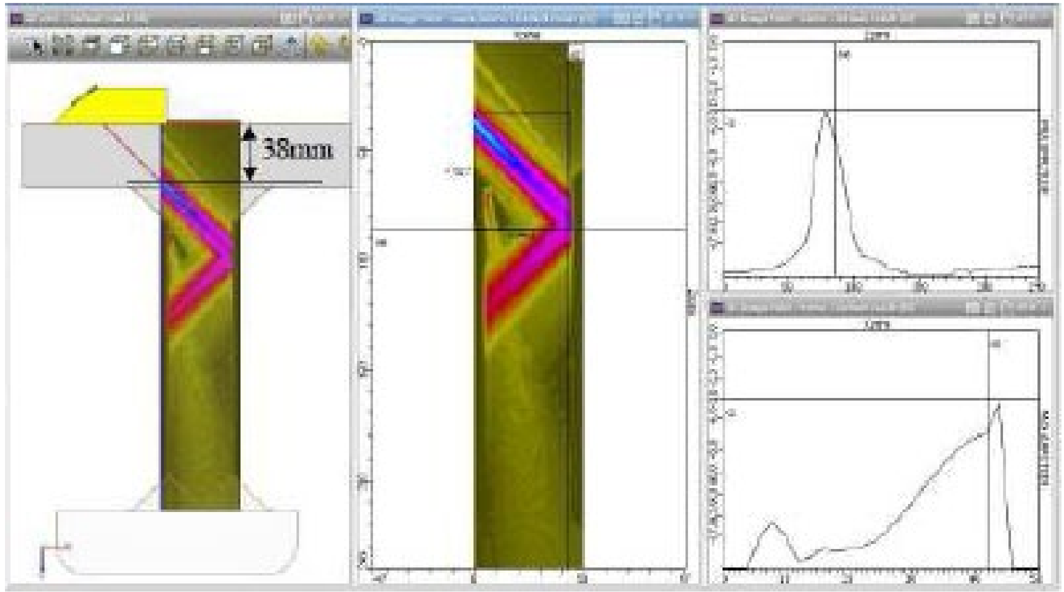
with welding joints described as homogenous medium

Scale 1 Design





Dedicated mockup
40mm thick
316L(N) welds



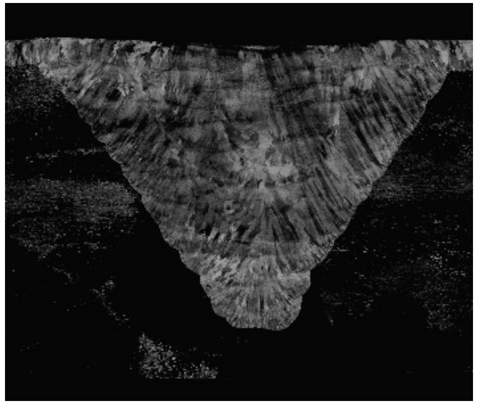
GEN IV International Forum
Expertise | Collaboration | Excellence

CIVA NDE 11

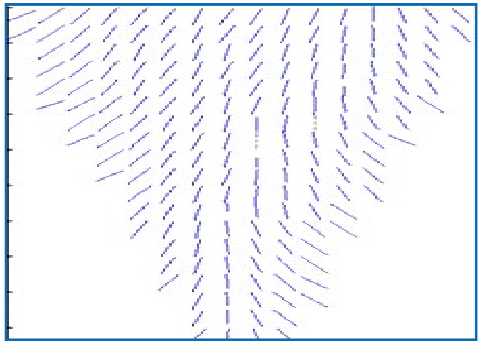
Structure Inspection: Control of Thick Welds with Ultrasounds

2017 - 2020

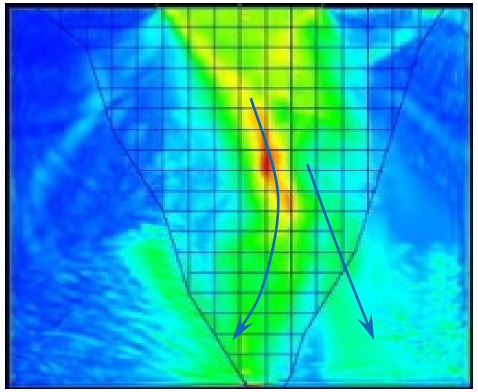
Modeling of austenitic welding grain structure



Being able to predict **ultrasound propagation**
in heterogeneous and anisotropic medium (welding joints)
Based on welding notebook (order of the passes, energy ...)



Understanding **macro-structure of multipass welds**
made by Gas Tungsten Arc Welding (GTAW)
Spatial distribution of grain growth - based on physical phenomena (thermal gradient, pass shape, ...)

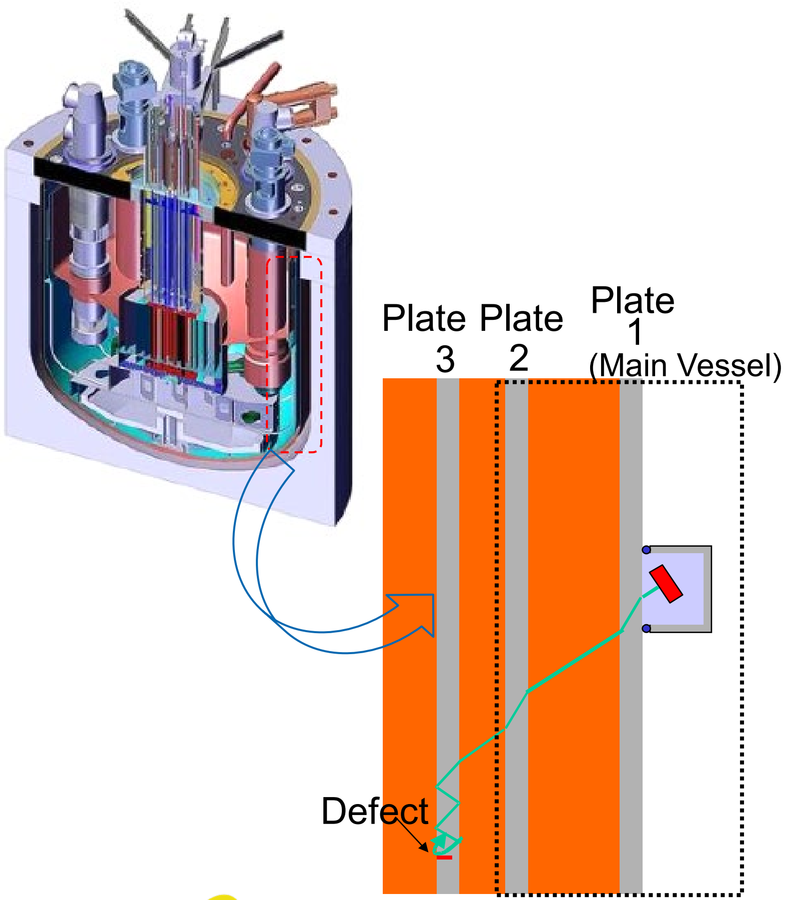


Qualification with experimental approach
on welded joint samples
made in a range of various welding specifications

GEN IV International Forum
Expertise | Collaboration | Excellence

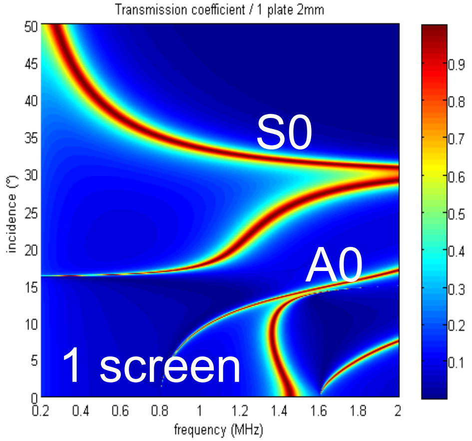
Control of Welded Joints of ASTRID Internals, from Outside

(through main vessel wall)

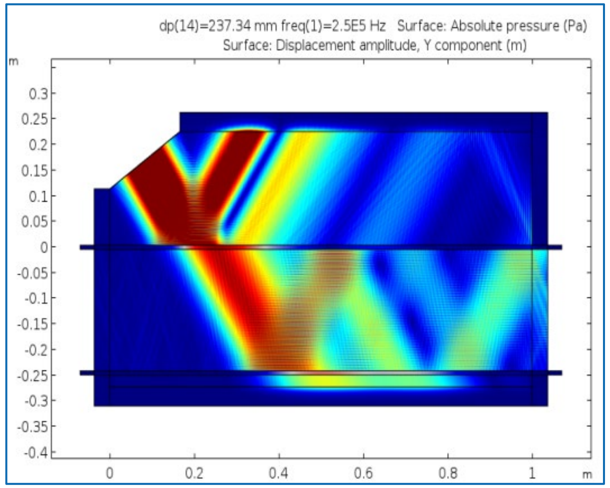


Ultrasonic Lamb wave propagation

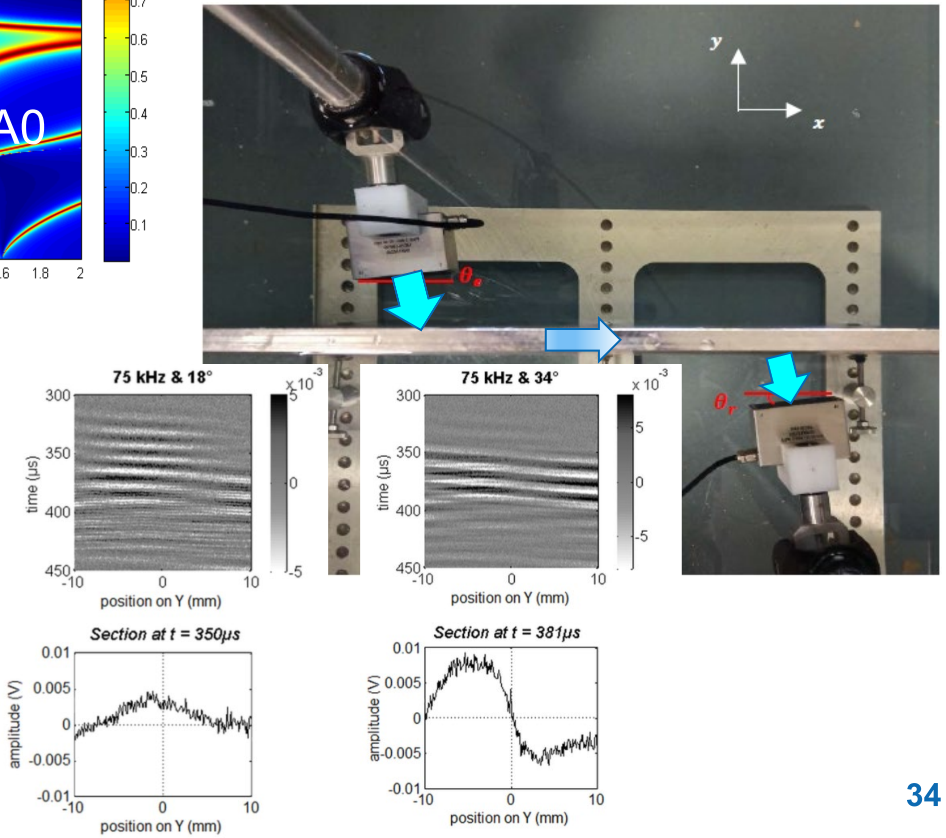
maximum transmission along various modes (S and A)



Simulation with COMSOL

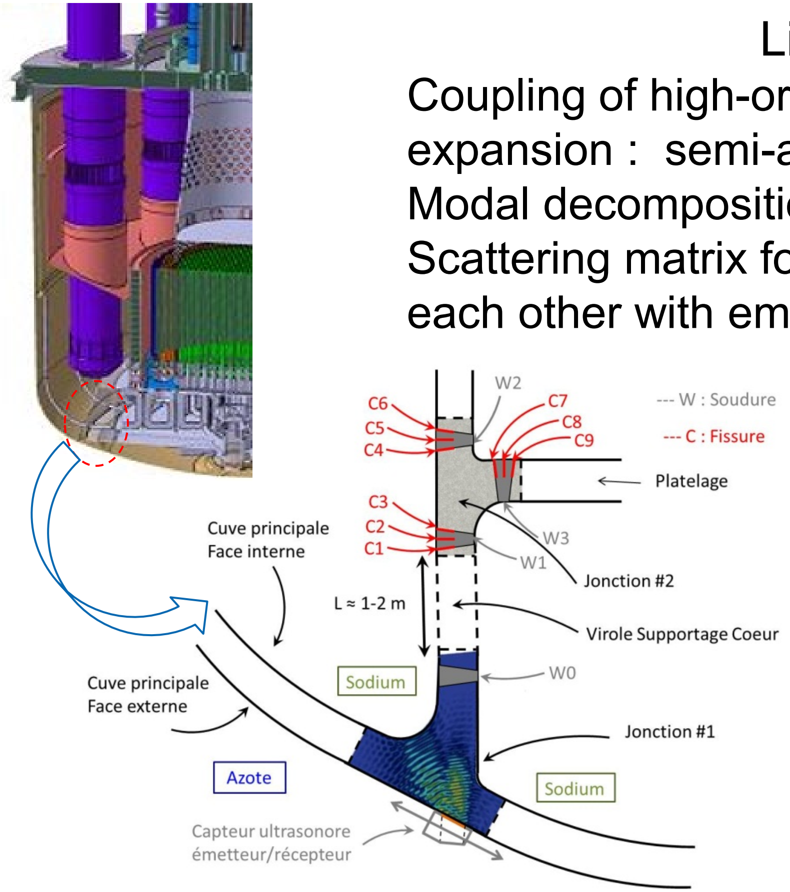


Under water feasibility tests



Control of Welded Joints Within the ASTRID Strongback Support Skirt,

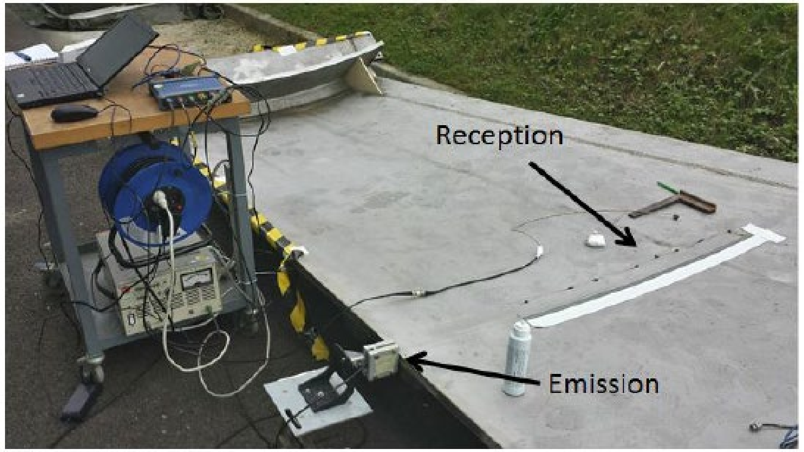
from outside (guided waves in support skirt)



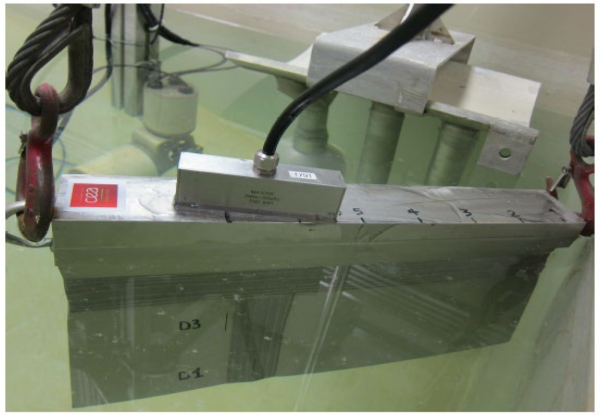
Linear Sampling Method

Coupling of high-order finite elements with a modal expansion : semi-analytical propagation along waveguide.
Modal decompositions.
Scattering matrix formalism to chain complex geometries to each other with emission and scattering phenomenon.

In air feasibility tests
on scale 1 mockup



Other approach:
simulation of bulk waves through the main vessel and plates, and all associated multiple echoes



In water tests

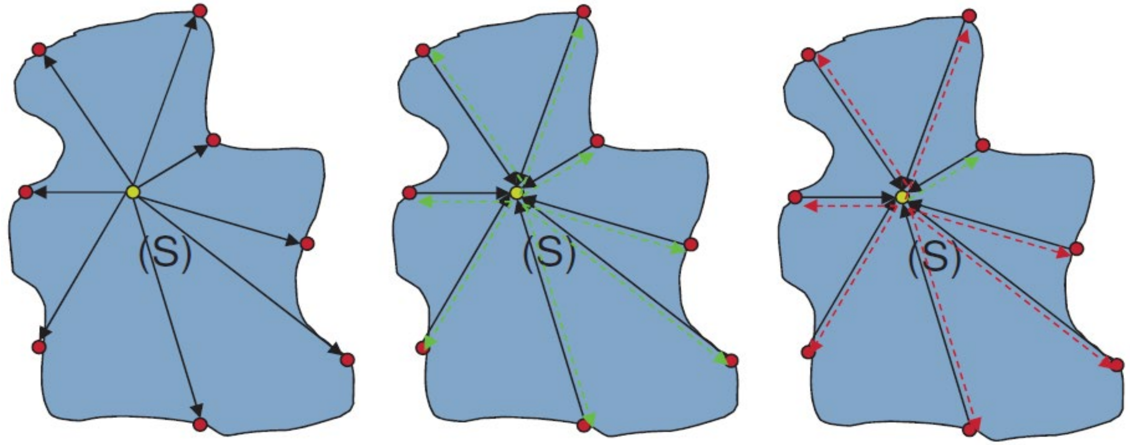
GEN IV International Forum
Expertise | Collaboration | Excellence

Under Sodium Non Destructive Examination
using time reversal technique

Structural Survey System (3S)

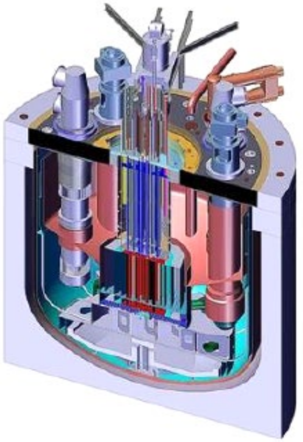
Surveillance of complex structure, using time reversed vibration waves propagation

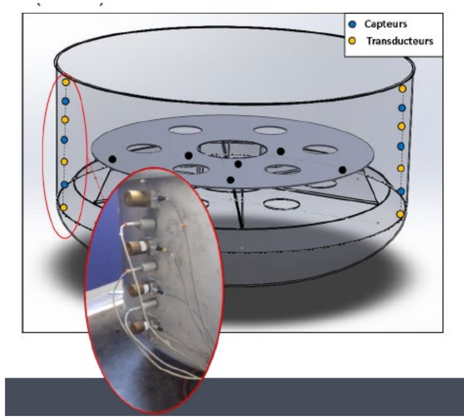
First stage	Second stage	Third stage
Learning	Focus	Surveillance

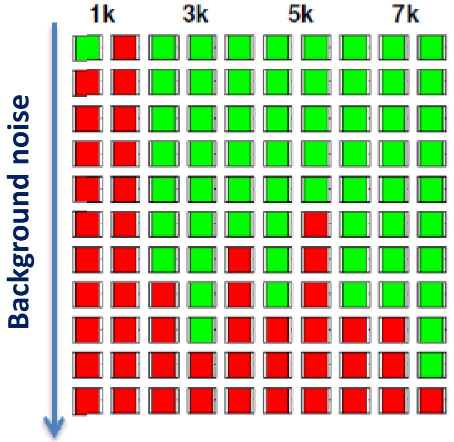


In red: sensors for emission and reception

Metravib
ACOEM Group







In water tests

1 meter long crack in ASTRID weld
↕
26 grams weight added

GEN IV International Forum
Expertise | Collaboration | Excellence

Repair with a Single Laser Tool

<u>Advantages</u>:

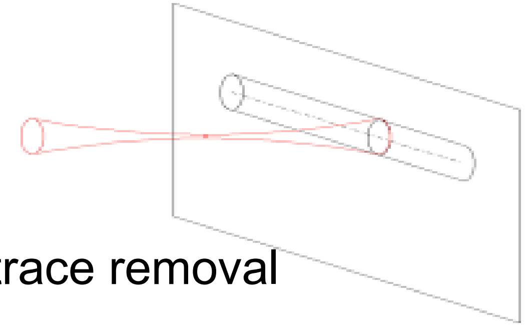
- Good feedback experience
- 3 applications : sodium removal + structure machining + welding
- No force
- Remote source (> 100 m)

<u>Drawbacks:</u>

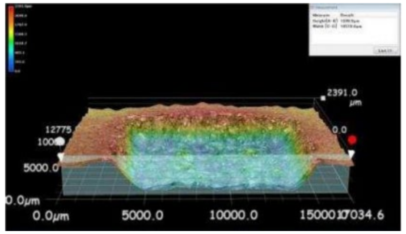
- Uncompatible with sodium
- Size and weight
- Stiffness of optical fiber

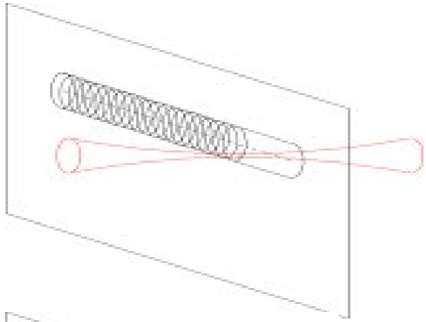
<u>Challenges:</u>

- Integration within a tight bell (see below)
- Compatibility with in sodium carrier
- Irradiation-proof (optical fiber)

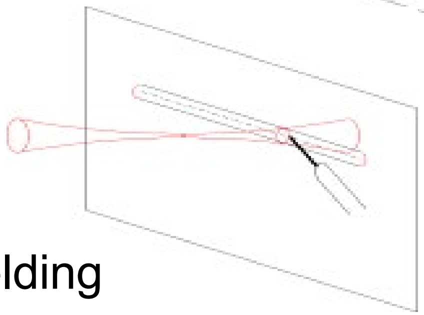


Sodium trace removal





Machining

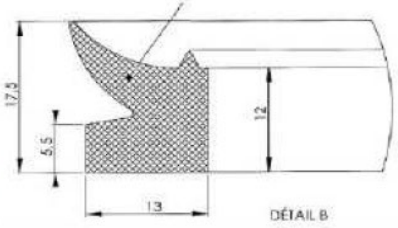


Welding

In-sodium Tightness, for No Contact with Sodium (repair tools, electrical cables and/or optical)

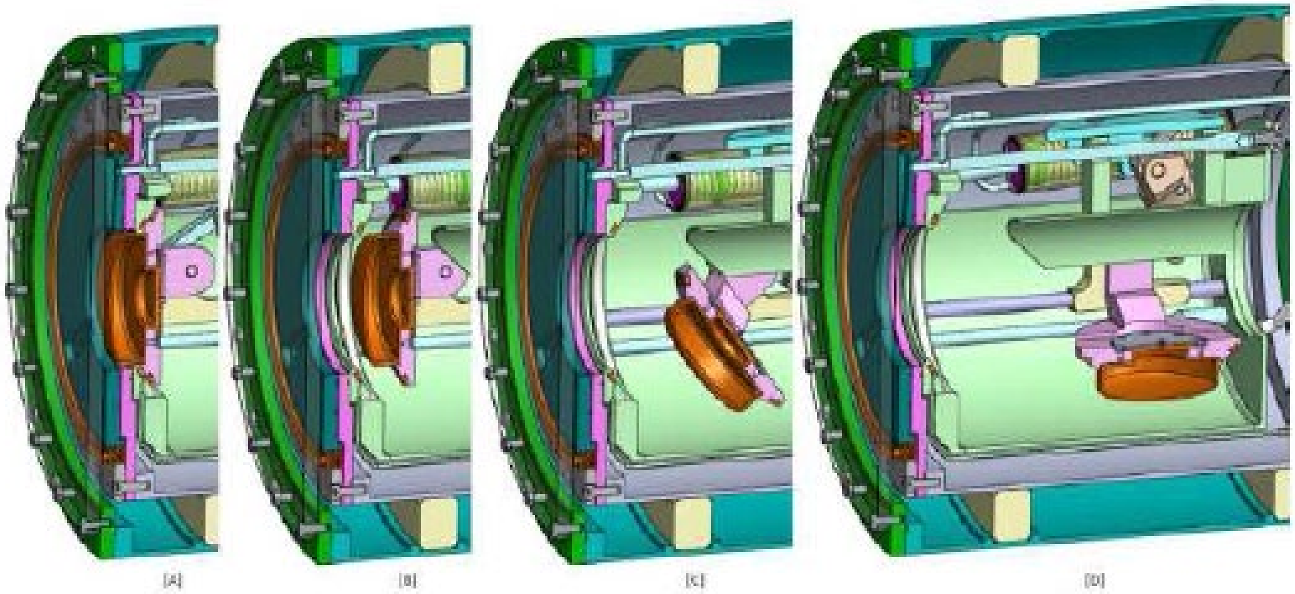
Material to be find for 200°C sodium sealing:

Profile of silicone sealing joint
for about 200°C operation in sodium



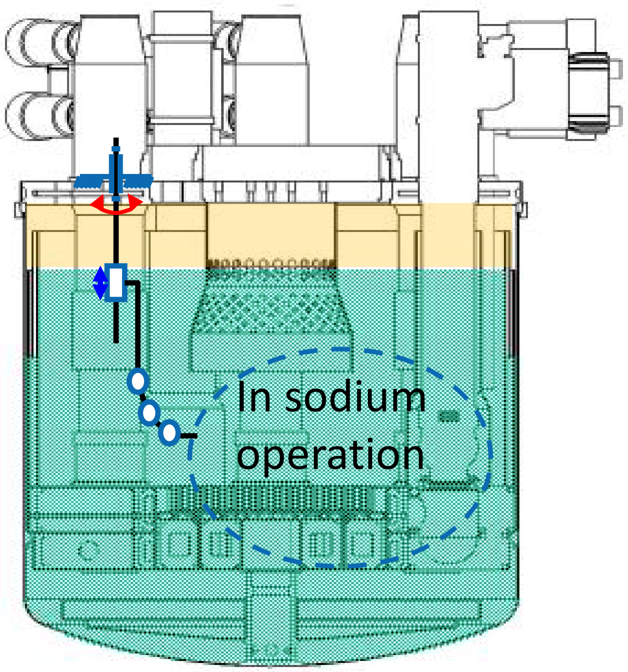
Design of a bell mounted on a remote handling device, for the **inspection & repair** tools which are foreseen to be embedded inside

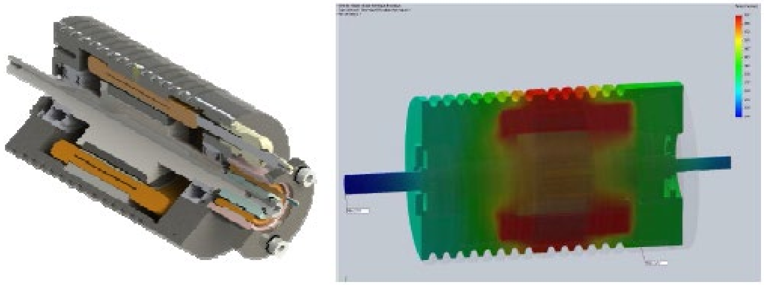
Kinematics of the bell shutter:
[A] Shutter closed, tight thanks to pressurized membrane
[B] Depressurization of membrane and opening of the shutter
[C] Removal of the shutter
[D] Shutter completely removed



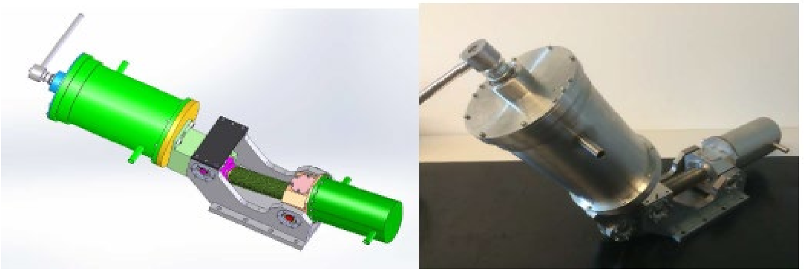
In-sodium Robotics

- ❑ Generic studies on robotics (in sodium or not);
- ❑ Associated means for testing (air/water/sodium);
- ❑ Case 1: main vessel inspection with robot in the gap between main and safety vessels (out of sodium);
- ❑ Case 2: sensor for steam generator tubes;
- ❑ Case 3: in sodium pushed chain type robot;
- ❑ Case 4: in sodium pole and cable type robot;
- ❑ Case 5: on-wheels robot for large in-gaz equipments;
- ❑ Case 6: robot for repair tools;





Prototypic brushless motor working at 200°C



Specific tight robot mockup with 2 degrees of freedom

- Gas-cooled fast reactor (GFR)
- Lead-cooled fast reactor (LFR)
- Molten salt reactor (MSR)
- Supercritical water reactor (SCWR)
- Sodium-cooled fast reactor (SFR)
- Very-high-temperature reactor (VHTR)

In Service Inspection and Repair Developments for SFRs
… and Extension to other Gen4 Systems

ISI requirements thanks to each national Nuclear Safety Authority

ISI requirement versus design margins
and consequences in case of a break (Risk Informed Method)

Design options for reaching ISI needs: size (number and length of welds), compactness, mechanical stresses (material), access for inspection (ports, removable components versus fixed structures), narrow gaps for free access around structures and components, modularity, coolant secondary loop …

- Pool-type of the primary circuit *versus* loop-type
- Large size *versus* smaller size (smaller is better?)

Inspection tools: available inspection sensors and techniques, and associated robotics (TRL)

Inspection conditions: medium (coolant), radiation, temperature, flows…

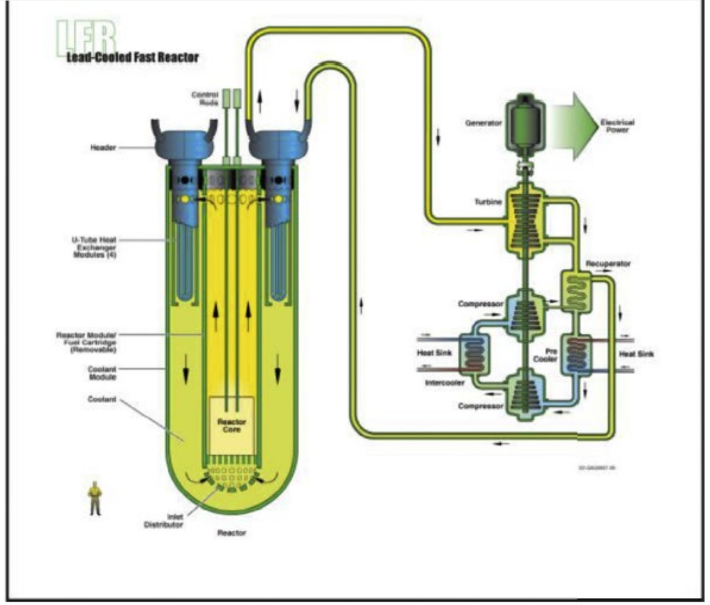
GEN IV International Forum
Expertise | Collaboration | Excellence

Ref. J.E. Kelly / Progress in Nuclear Energy 77 (2014) 240-246
Generation IV International Forum: A decade of progress through international cooperation
Table 4: Major R&D challenges and Technology gaps of the six generation IV reactor systems

- Lead-cooled fast reactor (LFR)

In Service Inspection and Repair Developments for SFRs … and Extension to LFR Gen4 System

System	Neutron spectrum	System pressure (MPa)	Coolant	Outlet temperature (°C)	Nominal power density (MW/m^3)	Size (MWe)
LFR (lead-cooled fast reactor)	Fast	0.3	Lead, lead/bismuth	480–800	70	20–1200



Cf J.E. Kelly:

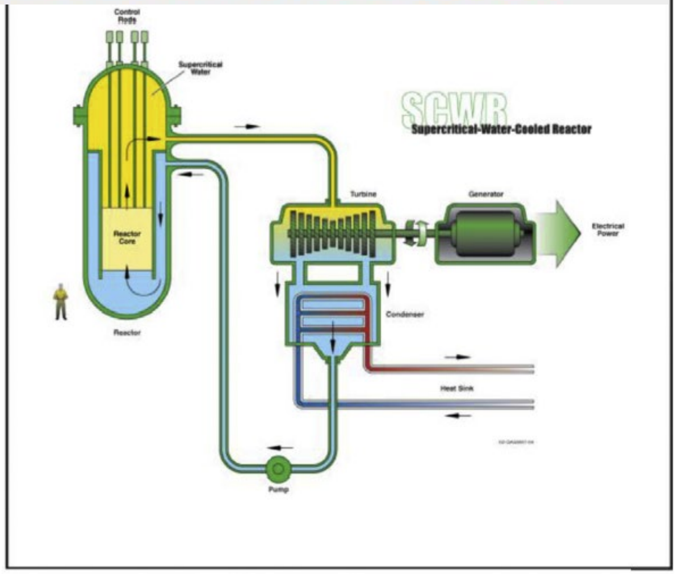
- ❑ *Corrosion control*
- ❑ *Core instrumentation*
- ❑ *Fuel handling*
- ❑ *Fuel development*
- ❑ *In-service inspection and repair techniques*
- ❑ *Seismic design*

- ➢ High density of Pb / PbBi (>10) → High buoyancy effect on any robotics
- ➢ 327°C Pb melting point (123°C PbBi) → High temperature conditions
- ➢ Chemical toxicity of Pb → Specific protection for operators
- ➢ Lead coolant is opaque → Ultrasonics for inspection
- ➢ Conditions for inspection? (Temperature/Pressure/Radiation…) → Wetting?
- ➢ High corrosion → Stainless steel surface of structures and components to be controlled (coating)?
- ➢ Cleaning if any removable components
- ➢ *Design to be adapted for inspection*

- Supercritical water reactor (SCWR)

In Service Inspection and Repair Developments for SFRs … and Extension to SCWR Gen4 System

System	Neutron spectrum	System pressure (MPa)	Coolant	Outlet temperature (°C)	Nominal power density (MW/m^3)	Size (MWe)
SCWR (super-critical water cooled reactor)	Thermal/fast	25	Water	510–625	100	1000–1600

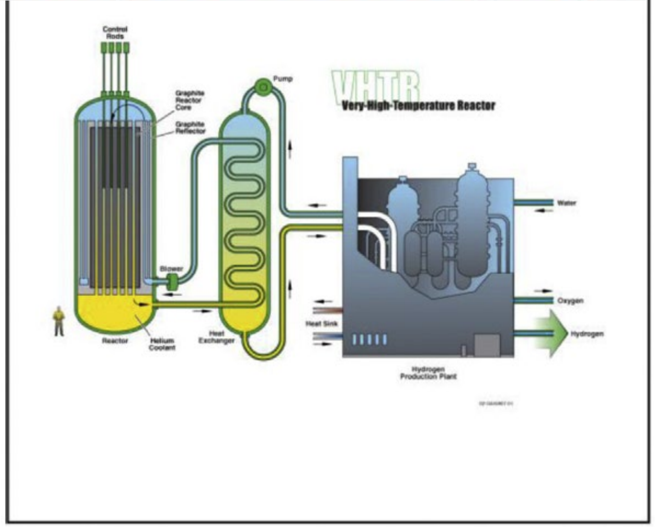


Cf J.E. Kelly:

- *Non-uniformities of local power and coolant mass flow rate*
- *High temperature cladding alloy development*
- *Identifying and managing safety system differences relative to conventional LWRs*
- *Water chemistry related to radiolysis and corrosive product transport*
- *Incompatibility of fast spectrum version with safety requirements*

- Supercritical conditions → Difficult to be maintained during inspection → Conditions for inspection? (Temperature/Pressure/Radiation…)
- Water coolant is not opaque → Optical inspection
- High pressure and temperature operating conditions → High stress for structures, then stronger inspection need?
- Easy removing if no supercritical conditions
- *Design to be adapted for inspection*

- Very-high-temperature reactor (VHTR)



In Service Inspection and Repair Developments for SFRs … and Extension to VHTR Gen4 System

System	Neutron spectrum	System pressure (MPa)	Coolant	Outlet temperature (°C)	Nominal power density (MW/m^3)	Size (MWe)
VHTR (very high temperature reactor	Thermal	8	Helium	900–1000	8	100–300

Cf J.E. Kelly:

- ❑ *Fuel qualification*
- ❑ *Development of composite components*
- ❑ *Pressure vessel materials*
- ❑ *Materials for heat utilization systems*
- ❑ *Qualification of graphite internals*
- ❑ *Balance-of-plant components for high temperature operation*
- ❑ *Hydrogen production subsystems*

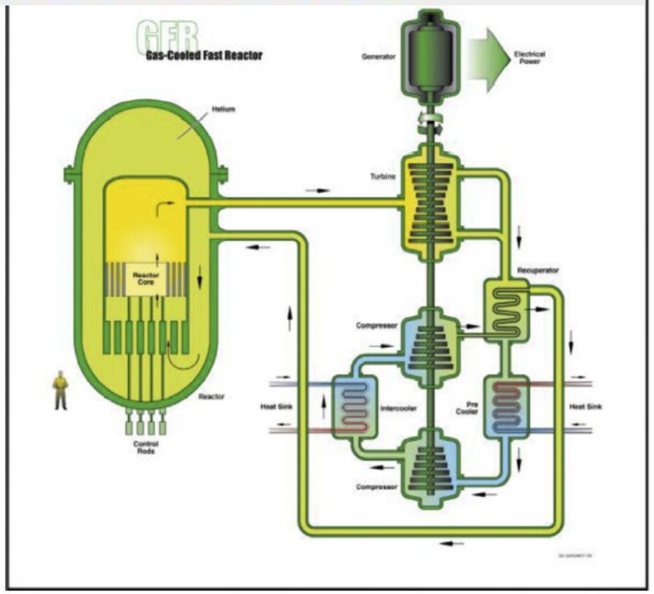
- ➢ High pressure and very high temperature operating conditions → High stress for structures, then stronger inspection need?
- ➢ Helium coolant is not opaque → Optical inspection
- ➢ Specific materials (composite) → Specific inspection methods to be developed and qualified
- ➢ Heat insulation → More difficult access?
- ➢ Conditions for inspection? (Temperature/Pressure/Radiation…)
- ➢ He inventory to be monitored if removing of components
- ➢ *Design to be adapted for inspection*

GEN IV International Forum
Expertise | Collaboration | Excellence

- Gas-cooled fast reactor (GFR)

In Service Inspection and Repair Developments for SFRs … and Extension to GFR Gen4 System

System	Neutron spectrum	System pressure (MPa)	Coolant	Outlet temperature (°C)	Nominal power density (MW/m^3)	Size (MWe)
GFR (gas-cooled fast reactor)	Fast	7	Helium	850	100	1000

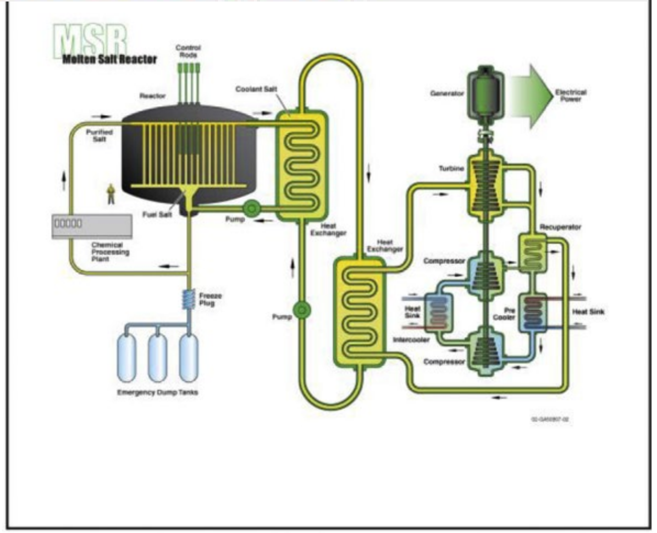


Cf J.E. Kelly:
- ❑ *Fuel capable of containing fission products at temperatures up to 1600°C for several hours*
- ❑ *Components for gas circulation*
- ❑ *Thermal barriers*
- ❑ *Valves and check valves*
- ❑ *Instrumentation*

- ➢ High pressure and very high temperature operating conditions → High stress for structures, then stronger inspection need?
- ➢ Helium coolant is not opaque → Optical inspection
- ➢ Specific materials (composite) → Specific inspection methods to be developed and qualified
- ➢ Conditions for inspection? (Temperature/Pressure/Radiation…)
- ➢ Heat insulation → More difficult access?
- ➢ He inventory to be monitored if removing of components
- ➢ *Design to be adapted for inspection*

In Service Inspection and Repair Developments for SFRs … and Extension to MSR Gen4 System

- Molten salt reactor (MSR)



System	Neutron spectrum	System pressure (MPa)	Coolant	Outlet temperature (°C)	Nominal power density (MW/m^3)	Size (MWe)
MSR (molten salt reactor)	Epithermal	0.6	Fluoride salts	700–800	170	1000

Cf J.E. Kelly:

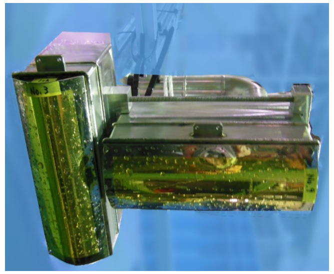
- ❑ *Physical-chemical behaviour of fuel salts*
- ❑ *Compatibility of salts with structural materials*
- ❑ *Instrumentation and control*
- ❑ *On-site fuel processing*

- ➢ Very high temperature operating conditions + fuel-salt → High stress and irradiation for structures, then stronger inspection need?
- ➢ Is salt coolant is opaque? → Optical inspection? / Ultrasonics
- ➢ Specific materials (compatible with salt) → Specific inspection methods to be developed and qualified
- ➢ Conditions for inspection? (Salt/Temperature/Radiation…)
- ➢ Heat insulation → More difficult access?
- ➢ Salt treatment if removing of components
- ➢ *Design to be adapted for inspection*

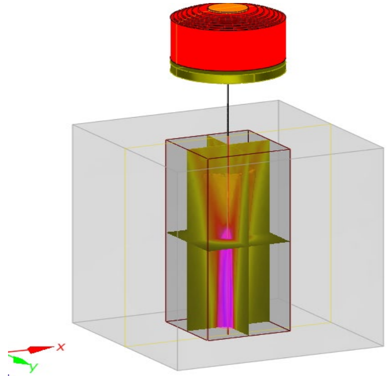
GEN IV International Forum
Expertise | Collaboration | Excellence

Conclusions and Perspectives

The R&D program launched by France for Inspection & Repair of Sodium Fast Reactors is on the way for technical demonstration capabilities in this harsh environment.
It has been strongly linked to ASTRID prototype design, from 2010 to 2019.



Development of ultrasonic transducers for telemetry, imaging, Non Destructive Examination: piezoelectric and electromagnetic concepts for operation at about 200°C in liquid sodium

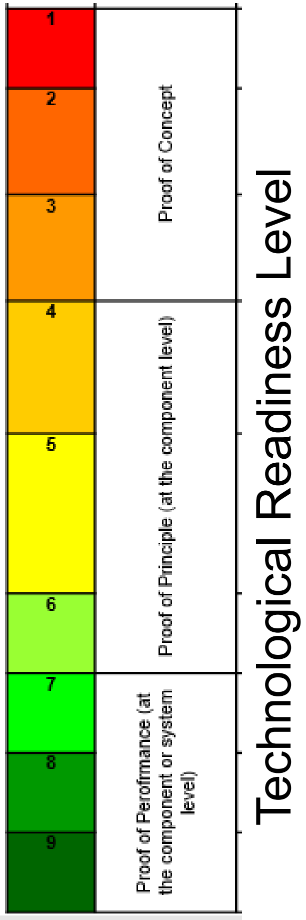


Development and qualification of Non Destructive Examination techniques: extensive simulation with CIVA software platform and experimental testing (under water and under sodium)

Development of robotics for large reactor vessel: generic studies for associated materials and specific concepts

GEN IV International Forum
Expertise | Collaboration | Excellence

Conclusions and Perspectives

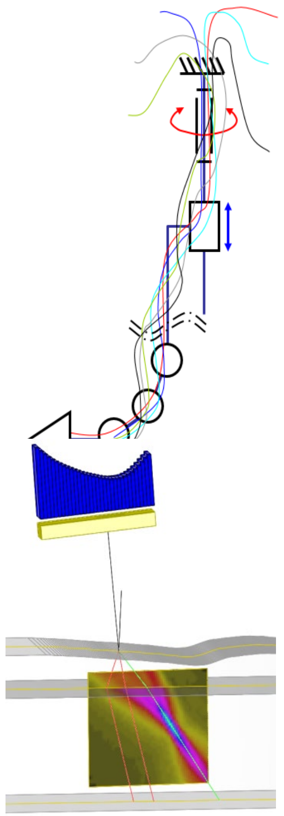


Key milestones of this ambitious R&D program

- Validation of **ultrasonic transducers** for under sodium conditions (TRL 4 → 6)

- Development and qualification of ultrasonic **inspection techniques** (NDE, telemetry, and imaging) under sodium conditions (TRL 4 → 6)

- Definition of key components of the **robotic equipment** for operation in 200°C liquid sodium (TRL 4 → 5)



… and don't forget inspection need,
to be taken into account
from the very beginning of Preliminary Design phase!

A special thanks to French colleagues working at:

CEA	Cadarache	(ISI&R Strategy, Specifications, under water and sodium tests, High Temperature Ultrasonic sensors, NDE, Imaging, Technology)
CEA	Saclay	(CIVA simulation, under water tests, EMAT sensors, Robotics)
CEA	Pierrelatte	(Under sodium tightness)
FRAMATOME	Lyon	(SFR Design, ISI&R Strategy, Robotics)
FRAMATOME NDE Solutions	Chalon/Saône	(NDE in sodium sensors)
EDF	Chatou and Renardières	(Robotics, NDE)
CNRS	Aix and Marseille	(Ultrasonic imaging, NDE)
AMU	Aix and Marseille	(Ultrasonic imaging, NDE)

Associated Bibliography: non exhaustive list…

Science and Technology of Nuclear Installations: Development of Tools, Instrumentation and Codes for Improving Periodic Examination and Repair of SFRs, F. Baque et al., Hindawi Publishing Corporation,, Volume 2012, Research Article ID 718034 (2012)

Special issue of Sensors (2019): Sensors for Ultrasonic Nondestructive Testing (NDT) in Harsh Environments

- Manuscript ID: sensors-592968, Design of a phased array EMAT for inspection applications in liquid sodium, Laura Pucci, Raphaële Raillon, Laura Taupin, François Baqué
- Manuscript ID: sensors-593676, Ultrasonic transducer for non-destructive testing of structures immersed in liquid sodium at 200 °C, Jean-Francois Saillant, Régis Marlier, Frédéric Navacchia, François Baque
- Manuscript ID: sensors-595263, 2D ultrasonic antenna system for imaging in liquid sodium, Léonard Le Jeune, Raphaële Raillon, Gwénaël Toullelan, François Baqué, Laura Taupin

Int. Conf. ICAPP (2010 to 2019)

Int. Conf. FR’09 Kyoto, FR’13 Paris, FR’17 Ekaterinbourg, FR’22 Beijing

Int. Conf. ANIMMA 2009, 2011, 2013, 2015, 2017, 2021: 21 papers and posters

Int. Conf. ICU, IUS, QNDE…

Upcoming Webinars

Date	Title	Presenter
27 July 2021	Evaluating Changing Paradigms Across the Nuclear Industry	Dr. Jessica Lovering, Carnegie Mellon University, USA
26 August 2021	Graded Approach: Not Just Why and When, But How	Mr. Vince (Alois) Chermak, INL, USA
23 September 2021	Experimental R&D in Russia to Justify Sodium Fast Reactors	Dr. Julia Kyzina, IPPE, Russia