Design of an acoustic sensor for fission gas release characterization devoted to JHR environment measurements

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• Presentation of the group of partners and the project
• Chronology of the work on the gas composition devices
• Operating principle of the device
• Device design
• Device characterization
- Measurement of the PCI (Pellet Cladding Interface) by acoustic imaging
- Mechanical characterization of irradiated fuel
- Estimation of the pressure and composition of a gas confined in PWR tube
- Measurement of fission gas composition in experimental reactors
An experimental reactor is a nuclear installation in which we produce and maintain a chain reaction in order to obtain a flow of neutrons to be used during experimentation.

Some are used to study and qualify the behaviour under irradiation of structural materials and fuel.

Generally speaking, an experimental reactor requires instrumentation (temperature, inner pressure, chemical properties, structural evolution...)

The aim of the partnership between CEA and IES (Institute of electronic and systems) is to develop a means of measuring the gas composition in a fuel rod for an experimental reactor.
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2010: Testing the gas composition sensor (CACP-1 REMORA 3) in OSIRIS [2]

2011-20XX: Study of a new gas composition sensor with high temperature (\(< 300^\circ C\) )

- Acoustic sensor overview of CACP-1 2010 tested in OSIRIS [1]
- SEM picture × 5000 of high Curie temperature piezoelectric material PHD of F. Very and O. Gatsa
- Raw signal in 90 Bar of helium and filtered signal by FFT[2]
- Variation of gas composition during maximal irradiation phase [2]
- Irradiation study of piezoelectric elements at high Curie temperature (Animma 2019) [3]
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Acoustic sensor for gas composition measurement (REMORA3 generation)

Filtered signal by FFT and RFFT

Echogram in Helium under pressure

schematic sectional view of the CACP 1 device

- Brahing
- PZT OR NBT
- Stainless steel plate
- Airtight weld seam
- Acoustic cavity
- Fission gases from the plenum
- Deflector

Echogram in Helium under pressure

- First echo
- Second echo
- Third echo

Filtered signal by FFT and RFFT

- 61 bar
- 58 bar
- 48 bar
Then how pass from $\Delta t$ to a gas composition measurement?

Dependency of acoustic celerity and the molar mass of the gas

$\displaystyle c = \sqrt{\frac{\gamma RT}{M}}$

With $\displaystyle c = \frac{2d}{\Delta t}$

Standard Acoustic measurements from gas cavity

-61 bar
-58 bar
-48 bar

- First echo
- Second echo
- Third echo

Equation of statistical physics linking the velocity of acoustic waves to a gas composition

Perfect gas = use the first order Viriel equation

$\displaystyle c^2 = \frac{RT}{M} \left(1 + 2b \frac{a}{RT} \frac{1}{D} + 3b^2 D^2 \right)$

Real gas = use either the Viriel or Redlich-Wong equation

$\displaystyle c^2 = \frac{RT}{M} \left(1 + 2b \frac{a}{RT} \frac{1}{D} + 3b^2 D^2 \right)$

- The ratio $\frac{x_{Xe}}{x_{Kr}}$ is known (12 for UO$_2$ and 17 for MOX)
- We have to know the initial gas mixture (100% He for instance for $t=0$)

Estimation by equations of the ratio $x$ between He and Xe/Kr

Decrease of the speed of sound for a real mixture
Because the GEN1- REMORA3 sensor presents some limitations:

- Mechanical coupling imperfection between the active element and substrate
- Parallelism issue due to fabrication technique
- Temperature limitation of an active element (PZT) at 200 °C → The NBT have an higher temperature limitations

Two thesis (2015 - F. VERY & 2018 - O. GATSA) allowed us to propose two solutions:

- Direct screen printing of an active element onto alumina substrate to reduce the imperfection and non-parallelism influence
- Active element with a working temperature about 400 °C
- Both of these solutions have been validated under nuclear radiations [3]

My work consists to design, manufacture the new Acoustic instrumentation and GEN2- sensor

Now we have to study the structure of the device...
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Device specifications

- Resist to a temperature of at least 350 °C for Gen2-sensor → Use of ceramics and refractory cement for the manufacturing of the devices

- Radiation constraints → Experiments have been done so as to test the NBT under harsh environment (Neutron flux, temperature...) (ANIMMA 2019)

- Dimensional constraints → must be able to fit in a cylinder of 15 mm diameter

![Diagram of new instrumented fuel rod for JHR](image)
Fabrication of the piezoelectric part

1. Powder of NBT
2. Mixed powder + binding agent
3. Screen printing deposition
4. Firing
5. Polling step

isostatic pressing
- Use of NBT (Sodium Bismuth Titanate) similar to PZ46 marketed by MEGGIT® (no longer commercialize) → Has a high Curie temperature and a sufficient S/N ratio for our applications (at least 350° C)

- Fabrication of matrix plates 8 piezoelectrics elements by screen printing

- Use of Pt and Au electrodes that can reach temperatures of at least 1000 ° C

- Ceramic disk with piezoelectrics parts

- SEM pictures of our NBT

- SEM pictures of marketed PZ46® from MEGGIT®

- Screen printing on MACOR and Alumina (Al₂O₃)
The sensor Body is made of vitroceramic MACOR for two reasons:

- Low mismatch of TCE between elements of the sensor ($\alpha_{\text{Al}_2\text{O}_3} = 8.6 \times 10^{-6} \text{ K}^{-1}$ VS $\alpha_{\text{NBT}} = 7 \times 10^{-6} \text{ K}^{-1}$ VS $\alpha_{\text{MACOR}} = 9 \times 10^{-6} \text{ K}^{-1}$)

- Each parts can be bounded by alumina cement (resilient until $T_{\text{max}} = 1400^\circ\text{C}$)

Integration of the sensor directly in the pressurized cavity.
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• **Device characterization and results**
First of all, for characterization in a viscoelastic medium like gas, the resonance must be around 5 MHz:

- With a numeric model (KLM), we have estimated optimals dimensions and thickness for the sensor.

- For a 700 µm thickness alumina substrate and 90 µm NBT element the fundamental should be around 5 MHz.
The preliminary tests consist in filling the device with ethanol in order to use it as propagation medium:

- **Decrease of echoes → Good parallelism**
- **Good S/N ratio for liquid medium**

![Graph showing acoustic reflexions in ethanol medium](image)

**7 acoustic reflexions in ethanol medium and the next measurements in pressurized He**
The acoustic team of *IES* and *TMI Orion* have developed a specific pressurized test bench for our laboratory:

- Possibility to be use up to 200 Bar for $T=200\,^\circ\,C$
- 4 sealed contacts permitted to connect 1 thermocouple and 1 acoustic sensor

The first experiment under gas pressure are planned for this summer.
Conclusions

- NBT seems to be a suitable material for the realization of this new device
- the new sensor will have a 100% ceramic composition
- Preliminary tests with ethanol have been successful and are promising for the future of the project
Bibliographie