Acoustic sensors devoted to non-destructive fission gas characterization of LWR nuclear rod in hot lab facilities

J.Y. Ferrandis [1,2], E. Rosenkrantz[1,2], G. Lévèque [1,2]
V. Auret [3], R. Blachier [3]

[1.] **University Montpellier, IES, UMR 5214, F-34000, Montpellier, France**
[2.] **CNRS, IES, UMR 5214, F-34000, Montpellier, France**
[3.] **EDF SEPTEN, Avenue Antoine Dutrievoz, F-69100 Villeurbanne, France**

ABSTRACT

Our group is now working for more than 15 years, in a close partnership with EDF on the development of acoustic sensors devoted to the characterization of fission gas.

We developed a non-destructive device that can be directly applied on a LWR fuel rod [1]. The problem to be solved relates to the measurement of the fission gas pressure and composition in a fuel rod using a non-destructive method. Fuel rod internal pressure is one of the safety criteria applied in nuclear power analyses. This criterion must be verified in order to avoid any fuel-cladding gap reopening risk and therefore any local clad ballooning. Apart from the safety implications, this parameter is also a fuel behaviour indicator and reflects the overall fuel performance in operation, but also during shipping and long-term storage. Rod internal pressure is one criterion amongst others, like cladding corrosion, against which the acceptable fuel burn-up limit is set. Up to now, any other non-destructive method can be proposed.

We presented in 2010 [1] an acoustic method to assess the pressure and the composition of the internal gas mixture of a standard LWR fuel rod. A piezoelectric transducer, driven by a pulse generator, generates the acoustic waves in a cavity that may be the fuel rod or a chamber connected to an instrumented rod. The composition determination consists in measuring the time of flight of the acoustic signal emitted. The pressure can be estimated by a calibration process, above the measurement of the amplitude of the signal. A full-scale hot cell test of this acoustic method was also carried out successfully on irradiated fuel rods in the LECA-STAR facility at CADARACHE Centre.

We have developed an improvement of this sensor allowing us to divide by two the uncertainty on the pressure measurement. In the case of hot-cell measurements, viscous liquid can be used to couple the sensor with the rod. For gas content with a pressure exceeding 15 bars and a 10% Xe/Kr ratio, such coupling may reduce relative acoustic method accuracy by ±7% for pressure measurement result and ±0.25 % for the assessment of gas composition.

The transducer and the associated methodology are now operational for non-destructive measurements in hot lab facilities and allow characterising the fission gas without puncturing the fuel rods.

INTRODUCTION

We developed a non-destructive acoustic method allowing measurement of the pressure and the composition of the internal gas mixture in the upper plenum of a standard LWR fuel rod. The sensor is in contact with the fuel rod (Fig. 1). It injects an acoustic pulse in the gas through the cladding. The signal received by the transducer after a back and forth path of the sound wave through the gas is the analysed [2].

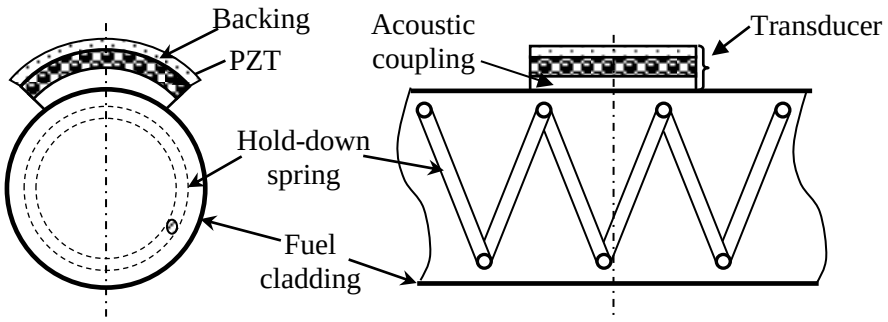

Figure 1. Schematic representation of measurement process, tube inner diameter D=8.36 mm and tube thickness e=57 mm (from [1]).

Non-destructive methods coexist to assess the internal gas pressure, e.g. measurement by gamma scanning of ^{85}Kr, which requires heavy devices [3, 4] but there is no easy and accurate non-destructive method for characterize the fission gas (pressure and composition) without puncturing the rod in a hot cell.

A full-scale hot cell test of sensor was carried out successfully between 2008 and 2010 on irradiated fuel rods in the LECA-STAR facility at CADARACHE Centre and an improvement of the method was done to increase the sensitivity on the pressure measurement.

The transducer and the associated methodology are now operational for non-destructive measurements in hot lab facilities and allow characterising the fission gas without puncturing the fuel rods.

PRINCIPLES OF MEASUREMENTS

A piezoelectric transducer excites the pressurised gas mixture and allows measuring frequency spectrum the vibrations of the gas.
The acoustic impedance of a gas in a rigid plane cavity is a periodic function. The gas resonances are spaced by a frequency period $\Delta f = c_{gaz}/2D\,(Hz)$, where D is the inner diameter of the fuel rod and c_{gas} *is* the speed of sound in the gas mixture. As a result, the speed of sound can be computed from $c_{gaz} = 2D\Delta f$ and the molar mass M (kg/mol) of the mixture can then be deduced:

$$M = \frac{\gamma RT}{c_{gas}^2} \quad and \; M = xM_{xe} + (1-x)M_{He} \qquad (1)$$

R is the universal gas constant, 8.314 $J.K^{-1}.mol^{-1}$
γ is the adiabatic index, 5/3 for a monoatomic gas

In the above expression the gas is assumed to be mixture of helium and xenon, x is the molar fraction of xenon. The temperature T (K) was measured independently.

When a small amount of krypton is present, the above molar mass express:

$$M = xM_{Xe} + \frac{x}{17}M_{Kr} + \left(1 - x - \frac{x}{17}\right)M_{He} \qquad (1)$$

The ratio of the concentration of xenon to the concentration of krypton is assumed to be equal to 17 ($x_{Xe}/x_{Kr} = 17$) for the measured fuel rods. This assumption is true after the first fuel cycle. It results from measurements carried out by the CEA on several equivalent fuel rods (which have mainly equivalent initial *Pu* rate) and confirms previous works [5].
Within the range of pressure of the testing (0-150 bars) some corrections must be made accounting that the mixture of He-Xe is not a perfect gas (the speed of sound increases with the pressure), suitable corrections must be performed [6]:

$$c_{gas}^2 = \frac{5RT}{3M}\left[1 + \left(2b - \frac{a}{RT^{3/2}}\right)\frac{P}{RM}\right] \qquad (2)$$

where P is the pressure and the adjustable quantities *a* and *b* are obtained by fitting data from the work of J.J. Hurly [7].
The amplitude of gas resonances in frequency spectrum and of echoes in echogram increases with the pressure. This phenomenon makes it possible to determine the pressure via a calibration process.

HOT-CELL ADAPTATION

A specific sensor has been designed for an easy use in the hot cell. The specificities do not concern the acoustic part of the sensor but the use of LEMO connector and an auto-positioning system.

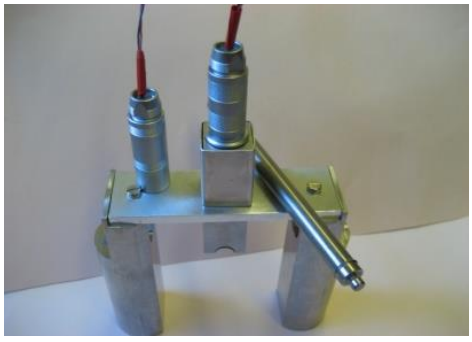

Fig. 2. A specific acoustic sensor for hot cell measurements including auto-positioning system and LEMO connector from [6].

An auto positioning system has been proposed to ensure the repeatability of the coupling between the tube and the sensor. It consists in two metallic masses tied to the sensor. With these two masses, the centre of gravity of this heavy system is under the rod : It gives a good stability and a constant coupling force between the sensor and the rod. Besides, the large size of this system allows handling the device using the tele-manipulators fitted to the hot cell.

We presented in [8] an application of the acoustic method to assess the pressure and the composition of the internal gas mixture of a standard LWR fuel rod. With a transducer called LMF6, it was possible to determine the composition with an uncertainty of about 1% and the pressure with an uncertainty of about 10 bars (for around 50 bars and a gas mixture containing 20% Xe/Kr). The limit of detection was established around 35 bars. A full-scale hot cell test of this acoustic method was also

carried out successfully on irradiated fuel rods in the LECA-STAR facility at CADARACHE Centre. The table I (from [8]) presents the results of the method compared to punctured tests for 7 fuel rods.

TABLE 1 - RESULTS OF THE ACOUSTIC METHOD COMPARED TO PUNCTURE TESTS IN 7 IRRADIATED FUEL RODS (MARCH 2008 - APRIL 2010) FOR THE COMPOSITION AND PRESSURE DETERMINATION

Rod no / Date	Composition (x_{Xe}) and Pressure	
Acoustic results		Puncture Results
1 / March 2008	34.4 ± 0,5 % 61 ± 6 bars	34.66 % [1] 61.5 ± 2.6 bars
2 / June 2008	17.6 ± 2.2 % 35 ± 6 bars	18.26 % 48.5 ± 2.3 bars
3 / October 2009 mean of 2 measures	21.5 ± 0.6 % 55 ± 6 bars	22.53 % 52.1 ± 2.3 bars
4 / October 2009	15.8 ± 0.8 % 52 ± 6 bars	16.33 % 44.5 ± 1.9 bars
5 / April 2010 mean of 5 measures	23.4 ± 0.3 % 44 ± 5 bars	24.1 % 47.3 ± 1.6 bars
6 / April 2010 mean of 8 measures	20.6 ± 0.3 % 45 ± 5 bars	20.4 % 45.3 ± 1.7 bars
7 / April 2010 mean of 3 measures	24.6 ± 0,3 % 42 ± 5 bars	24,6 48.8 ± 1.7 bars

These results were slightly interesting. A first conclusion is that the efficiency of the acoustic method is not altered by the irradiation time of two years in a LECA-STAR hot-cell, and possible modification of the cladding properties. A second conclusion is that the performances were good but had to be increased in order to be able to measure lower pressure and xenon concentration in Helium-Xenon mixture.

IMPROVEMENT OF THE SENSOR

The improvement of the sensor implies to better understand the vibrations of the system. When excited by a pulse, three kinds of vibrations appear: the transducer vibration (piezoelectric element, coupling layers, 1D-rod), flexural vibrations of the rod and the gas vibration, which has to be measured.

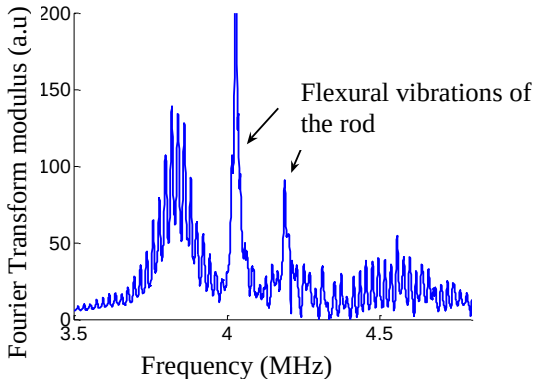

Fig. 3. Spectral response of the system between 3.5 and 5 MHz. The sharp peaks correspond to the gas resonance. The two flexural vibrations of the rod are the main parasites.

[1] The value of uncertainty linked to fission gas sampling and mass spectrometry is in the order of magnitude of ± 0.5%.

The three kinds of resonances are not at the same frequencies in the spectral domain and they do not have the same amplitude.

For instance in the case of a rod without a spring and for 150 bars pressurised gas, the resonances of the gas have a high amplitude which constitutes the major part the signal (Fig. 4a). Echoes are separated in time domain without any treatment. The gas signal is higher than the parasite. When the gas signal is low, a Fourier transform can separate parasites, filtering the domain of the flexural vibration of the tube. For instance, in figure 3, the zone between 4 and 4.2 MHz can be excluded. In figure 4b, the parasite (blue curve) is higher than the signal of the gaz. After a signal treatment, gas echoes appear (green curve).

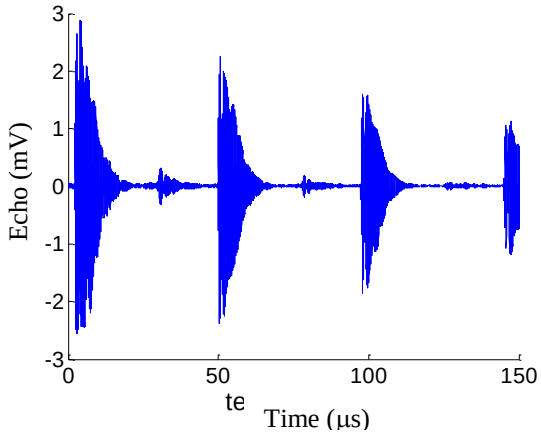

Fig. 4a. Time domain response for a rod without a spring and for 150 bars pressurised gas. The resonances of the gas have a high amplitude which constitutes the major part the signal. The echoes are separated from noise.

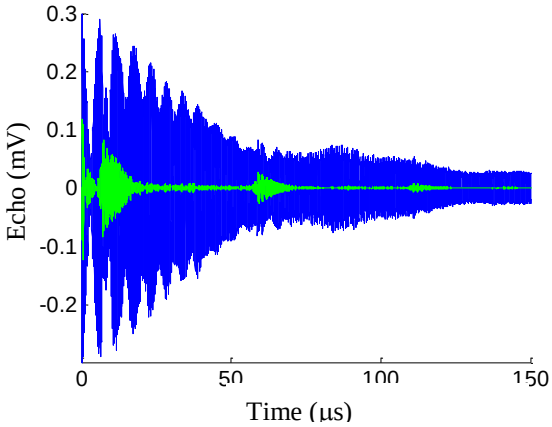

Fig. 4b. Time domain response in the case of the signal is low (blue curve). The echoes are in the noise. After a signal treatment, parasites are separated and gas echoes appear (green curve).

But such a treatment also excludes gas signal in the spectral zone which in not taken into account and may reduce the low limit pressure of measurement.

Then it appears important to physically reduce the amplitude of the parasite resonance and to optimize the signal to noise ratio, independently of the signal treatment. Two ways have been investigated :
- A new sensor design to shift of the resonance of the transducer in order to minimize the sensitivity in the parasite resonance zone.
- The choice of an acoustic coupling which quickly attenuates the parasite in time domain.

OPTIMISATION OF THE SENSOR DESIGN

The first step consists in designing a new. It consists in modifying the width of the matching layers. The minimum of the sensitivity to the gas has been put at the frequency of the parasite resonance.
The experimental responses are presented in the figure 5. We present the measured voltage (dB) versus frequency. Thin curves represent the raw response with the parasite resonance. The thick curves are interpolated responses. We can observe that the LMF10 response (new sensor) has a minimum of the sensitivity in the parasite resonance frequency domain but also present a higher sensitivity in the 4.5 MHz domain witch slightly increase the global sensitivity of the system.

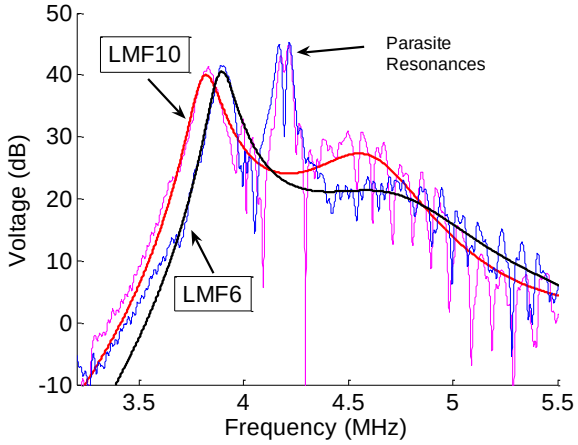

Fig. 5. Experimental response of LMF6 sensor (black curve) and LMF10 sensor (red curve).

This optimization of the sensor design increases performances by rejecting the parasite in a low sensitivity zone.

OPTIMISATION OF THE ACOUSTIC COUPLING

A second way to reduce the influence of the parasite is to use an acoustic coupling that physically attenuates the parasite.

As we can see on the figure 6, the time decay of the parasite when a viscous fluid is used as acoustic coupling is about 25 microsecond. Above this time, the noise keeps the same value and comes from electronic devices. In the case of water coupling, even above 80 microseconds, the parasite has not disappeared and so interfered with the gas signal. Indeed, the first echo of the gas appears after 40 microsecond (it obviously depends of the mixture) and its amplitude is lower than the noise amplitude.

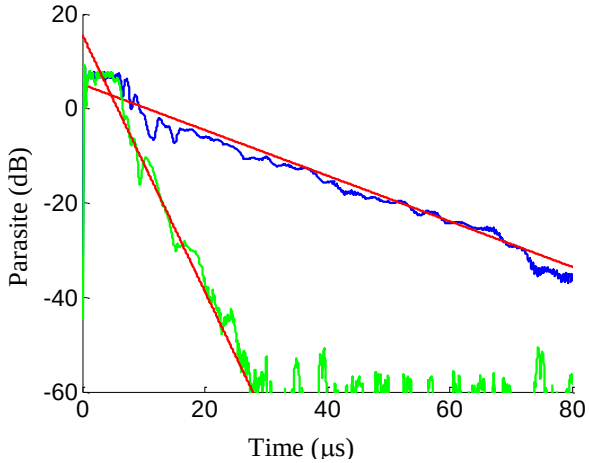

Fig. 6. Time decay of the parasite in the case of water coupling (blue curve) and of viscous fluid coupling (green curve).

Honey has been choose because it attenuates waves, especially shear waves. In the figure 6,the blue curves represent the raw signal in the time domain. In the case of water coupling, the parasite is high and last in time. In the case of viscous liquid coupling, at 45 microsecond, the parasite noise is pretty equal to zero and the raw signal is the gas signal.

FINAL PERFORMANCES OF THE METHOD

The improvement of the sensor allows us to decrease by two the uncertainty on the pressure measurement and to propose measurement even for pure helium. In the case of hot-cell measurements, viscous liquid can be used to couple the sensor with the rod.

The table II presents the performances of the method up today. These results are obtained from more than 500 measurements on gas mixture (pressure varying from 10 bars to 100 bars and composition from 0% of Xenon to 20%)

Table II : Final performances for a viscous coupling.

Composition	Low pressure limit (bars)	Pressure relative accuracy (σ) at 50 bars / at 20 bars	Composition relative accuracy (à σ) at 50 bars / at 20 bars
0 % Xenon	30	20 % / ---	0.5 % / ---
5 % Xenon	20	10 % / 20%	0,25 % / 0.5 %
10 % Xenon	15	10% / 15%	0,25 % / 0.5 %
Above 20 % Xenon	10	10% / 15 %	0,25 % / 0.5 %

In case of water coupling, the performances are slightly lower especially for low pressure and under 5% Xe concentration. But a specific signal treatment is under development.

Such performances, associated to specific instrumentation and signal treatment, now allow proposing our device as a new reliable instrumentation for gas characterization in hot-cell environment.

CONCLUSION

With the last generation of acoustic sensors devoted to characterization of fission gas, it was possible to determine the composition with an uncertainty of about 1% and the pressure with an uncertainty of about 10 bars (for around 50 bars and a gas mixture containing 20% Xe/Kr).
The improvement of this sensor allows us to decrease the lower pressure limit and the uncertainty on the pressure measurement. It also allows measurement from pure helium up to high xe concentration.

The method is now operational. It is a reliable non-destructive method for fission gas characterization (complementary to puncture tests) thatcan be added to non-destructive examination methods proposed in hot lab facilities.

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