ABSTRACT

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. 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 [2].

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.

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 directly in contact with the fuel rod (Fig. 1).

Several 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]. Other methods had been investigated
in the past, but no satisfactory solution has been proposed since; then there is no easy and accurate
non-destructive method for determining the fission gas internal pressure and gas composition without
puncturing the fuel rod in a hot cell.

Rod internal pressure is a safety criterion, such as e.g. cladding corrosion, giving the range for
using the fuel. These parameters constitute a fuel behaviour indicator and reflect the overall fuel
performance. Their knowledge is also required to validate engineering code simulations. These data
are currently assessed in hot cells.

Our method for pressure measurement has been developed since 1993. It consists in injecting
an acoustic pulse in the fuel rod through the cladding and in analysing the signal received by the
transducer after a back and forth path of the sound wave through the gas [5].
A full-scale hot cell test of the internal gas pressure and composition measurement by an acoustic sensor was carried out successfully between 2008 and 2010 on irradiated fuel rods in the LECA-STAR facility at CADARACHE Centre. The acoustic sensor has been specially designed in order to provide a non-destructive technique to easily carry out the measurement of the internal gas pressure and gas composition (mainly Helium-Xenon mixture, with a small amount of Krypton) of a LWR nuclear fuel rod. [6].

The representation of the device is described in Fig.1. The central frequency $f_0$ of the transducer is chosen to be equal to the first transparency frequency of the tube wall:

$$f_0 = \frac{c_D}{2e} = 4.14 \text{ MHz}$$  \hspace{1cm} (1)

where $c_D$ is the speed of the longitudinal wave in the metallic wall and $e$ its thickness. The thicknesses of the PZT transducer and of the clad are equal to half wavelength at the frequency $f_0$. Our sensor is efficient in the 3.5-4.5 MHz range. Several designs optimizing the sensor sensibility were found [7], depending on whether the gain, the bandwidth or both were considered. If the acoustic coupling is low impedance material as water or honey, the best solution is a $\lambda_0/2$ layer instead of the standard solution in $\lambda_0/4$ (Fig. 2).

![Figure 2. Comparison of the sensor sensibility obtained either with a $\lambda_0/2$ or $\lambda_0/4$ layer of water (theoretical results). For clarity the $\lambda_0/4$ curve has been divided by 4 to be in the same range to the $\lambda_0/2$ one. IE is the power injection efficiency and is representative of the sensor sensibility. (from [1]).](image)

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. 3. A specific acoustic sensor for hot cell measurements including auto-positioning system and LEMO connector from [6].](image)

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.

The method and the principles of measurement are widely discussed in [4, 5]. The speed of sound can be computed from the gas resonances period measured in frequency spectrum and the molar mass of the mixture, and its composition (volume ratio) can then be deduced. 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.

We presented in 2010 [1] 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 [2].

**IMPROVEMENT OF THE SENSOR**

When a voltage burst excites the system, 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.

![Fourier Transform modulus](image.png)

**Fig. 4.** 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.

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 of the signal (Fig. 5a). 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 4, the zone between 4 and 4.2 MHz can be excluded. In figure 5b, the parasite (blue curve) is higher than the signal of the gas. After a signal treatment, gas echoes appear (green curve). But the main problem with such a signal treatment is that it also excludes gas signal in the spectral zone which in not taken into account. The effect can be important in the case of low gas signal and it reduces 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. The improvement of the device consists in decreasing the influence of the parasite resonance on the measure. If we are able to separate the parasite resonance, we increase the useful signal. The main problem consists in rejecting a frequency domain in which the sensor is not very sensitive to the gas resonance. It will allow to increase the signal to noise ratio and then to get a lower limit for pressure measurement and a higher accuracy. 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**

A new sensor has been designed. 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. In the figure 6, we present the theoretical curve of the sensitivity to the gas of the sensor versus frequency. The blue curve is the response of the LMF6 sensor used in the past. The response is not so bad but it can be optimized by shifting the minimum of this curve to 4.14 MHz. It is the response of the red curve.

Fig. 5a. 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. 5b. 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).

Fig. 6. Sensitivity to the gaz of a new sensor (red curve) compared to the first one (blue curve). The peak of sensitivity has been shifted to minimize the influence of the parasites (around 4.14 MHz)
The experimental responses are presented in the figure 7. 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 which slightly increase the global sensitivity of the system. This modification of the sensor response allows increasing performances by rejecting the parasite in a low sensitivity zone.

Fig. 7. Experimental response of LMF6 sensor (black curve) and LMF10 sensor (red curve).

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. A viscous fluid has been chosen. As we can see on the figure 8, 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 on the mixture) and its amplitude is lower than the noise amplitude.

Fig. 8. Time decay of the parasite in the case of water coupling (blue curve) and of viscous fluid coupling (blue curve).

This phenomenon is lightly observed in the figure 9. 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. For instance
when the first echo should appear (red curve is obtained after separation of the parasite by Fourier transform treatment as presented before), the parasite widely interferes with the signal. In the case of viscous liquid coupling, at 45 microseconds, the parasite noise is pretty equal to zero and the raw signal is the gas signal.

Fig. 9a. LMF10 sensor time domain response in the case of honey coupling. Red curve is obtained after separation of the parasite

Fig. 9b. LMF10 sensor time domain response in the case of water coupling. Red curve is obtained after separation of the parasite

FINAL RESULTS

We have developed an improvement of the 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. These results are obtained above more than 500 measurements on gas mixture (pressure varying from 10 bars to 100 bars and composition from 5% of Xenon to 20%)

<table>
<thead>
<tr>
<th>Composition uncertainty</th>
<th>Pressure uncertainty (At 50 bars)</th>
<th>Low pressure limit</th>
</tr>
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<tbody>
<tr>
<td>Classical Sensor</td>
<td>± 1%</td>
<td>± 10%</td>
</tr>
<tr>
<td>New generation of sensor</td>
<td>± 0,25%</td>
<td>±7%</td>
</tr>
</tbody>
</table>

Table I. comparison of performances between classical and new generation of acoustic sensors.

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 limit of detection was established around 35 bars. Now, 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 improvement of
this sensor allows us to divide by two the uncertainty on the pressure measurement. Viscous liquid can
be used to couple the sensor with the rod.
Such improvement, associated to specific instrumentation and signal treatment, allows proposing our
device as a new reliable instrumentation for gas characterization in hot-cell environment.

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