A NEW PUNCTURING APPARATUS OPTIMISED FOR FREE VOLUME DETERMINATION

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L.DESGRANGES, F.DUJET & A.THOUROUDE
Commissariat à l'énergie atomique,
Centre d'études de Cadarache,
Saint-Paul-lez-Durance, France

Abstract

A new apparatus has been designed and manufactured which allows two determinations of free volume of PWR fuel rod. The apparatus, its operation and precision are presented. First results are presented. They demonstrate that the usual method provides results which vary with pumping time. The double expansion method, for which our apparatus is designed, has two advantages : it takes shorter time and provides more accurate results.

1. INTRODUCTION

Nowadays a large part of CEA hot cell job is devoted to high burn-up and MOX fuel characterisation. For these two types of fuel, Fission gas release is an important parameter to be measured [1] [2]. An accurate determination of internal gas pressure of fuel rod is then needed to define the best fuel operation conditions with regard to safety criteria. This determination is routinely performed in hot labs by rod puncturing, the measurement of rod gas quantity (either by pumping or by pressure measurement) and the measurement of rod free volume using the expansion of a known volume of gas into the previously pumped fuel rod. This method is accurate when all the gas content is actually removed from the fuel rod. For high burn-up fuel this assumption is not proved to be fulfilled : measurements performed within the Halden project [3] demonstrate that gas flow along the fuel rod is significantly reduced for high burn-up fuel. Moreover, optical examinations of French PWR high burn-up fuels showed that the gap between fuel and cladding is closed, filled by an internal corrosion layer [4], which reduces gas flow.

To improve the accuracy of free volume measurements for high burn-up fuels two approaches were explored. A theoretical approach led to a modelling of gas flow along the fuel rod : this point will be discussed in a further paper. An experimental approach led to design and manufacture of a new apparatus with two measurement methods of free volume : the usual method, described above, and the double expansion method. This last method takes benefit from the high pressure in fuel rod before puncturing to reduce the measuring time.

This paper describes this apparatus, its operation and accuracy. First obtained results are presented and discussed.

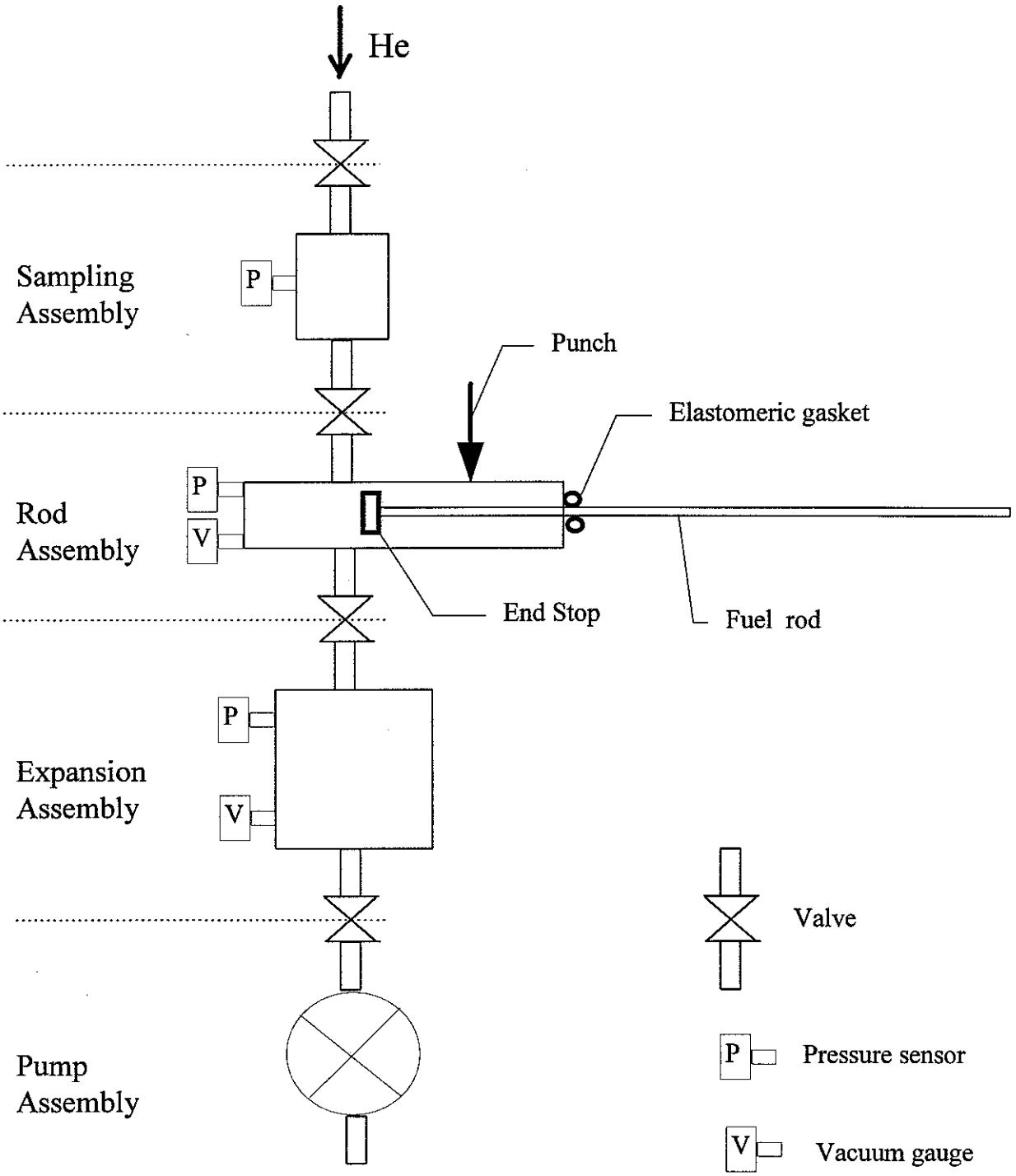


Figure 1 : schematic drawing of the new apparatus for free volume measurements

1. APPARATUS DESCRIPTION

The apparatus is settled in the CEA hot lab STAR, in Cadarache centre, in a concrete hot cell large enough to handle French PWR fuel rods. Its electronics and data acquisition systems are located in the front zone of the hot cell.

A schematic drawing of the apparatus is presented in figure 1. It is divided in four assemblies. Pump assembly is composed of a primary and a turbomolecular pump which allow a vacuum level of 10^{-5}-10^{-6} mbar in the expansion assembly. The other assemblies, namely sampling, rod and expansion assemblies are airtight linked vessels which can be isolated by valves.

The sampling assembly is designed to prepare a sample of Helium gas to perform free volume measurements following the usual method. Helium gas is injected in the sampling assembly with an appropriate circuit connected to an commercial Helium gas cylinder located outside the hot cell. The quantity of the Helium gas sample is measured using a pressure sensor. The volume of the vessel was designed to be approximately twice the free volume of French PWR fuel rod.

The rod assembly is designed for rod puncturing and pressure measurements. The top of the fuel rod, where its void volume is located, is moved into the rod assembly by an horizontal translation up to an end stop. Airtightness is obtained by pressing an home-made elastomeric gasket around fuel rod. Rod puncturing is achieved by hitting a punch with a falling mass of more than 2 kg. During puncturing the rod assembly is isolated from the other vessels. At this stage, the pressure in fuel rod is measured by a high pressure sensor.

The volume of the rod assembly is designed to be small and approximately equal to the free volume of French PWR fuel rods, so that the pressure measured in the rod assembly should be approximately half the internal pressure of the fuel rods before puncturing.

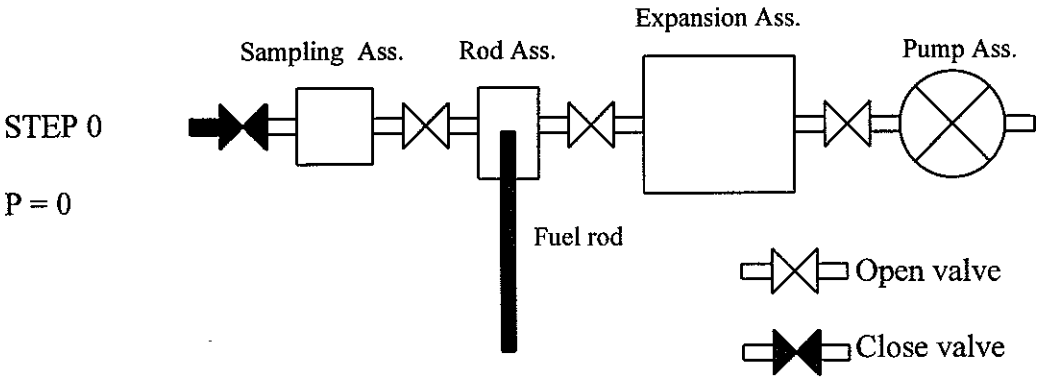
The expansion assembly is designed to make a second expansion of the gas from rod assembly to the expansion assembly. Its volume is chosen to have a low pressure after the second expansion, i.e. approximately two bars.

2. APPARATUS OPERATION

The apparatus operation is divided in three phases in which the rod assembly volume, the free volume of the fuel rod using the double expansion method and the free volume using the usual method are measured successively. Each phase is divided in steps. Each step corresponds to an equilibrium state of gas in the apparatus which will be represented by a schematic drawing. For each step, the pressure measurement is performed and pressure value is indicated on the drawing. For each phase a formula is given for the determination of the corresponding volume : these formulae use the pressure values of some steps and the volume values of the sampling, rod and expansion assemblies, designed as V_s, V_r and V_e respectively. The apparatus operation leads then to two values of the free volume V of the analysed fuel rod depending on the method, and to the value of the internal pressure P_0 of the fuel rod.

2.1 Phase 0 : fuel rod installation

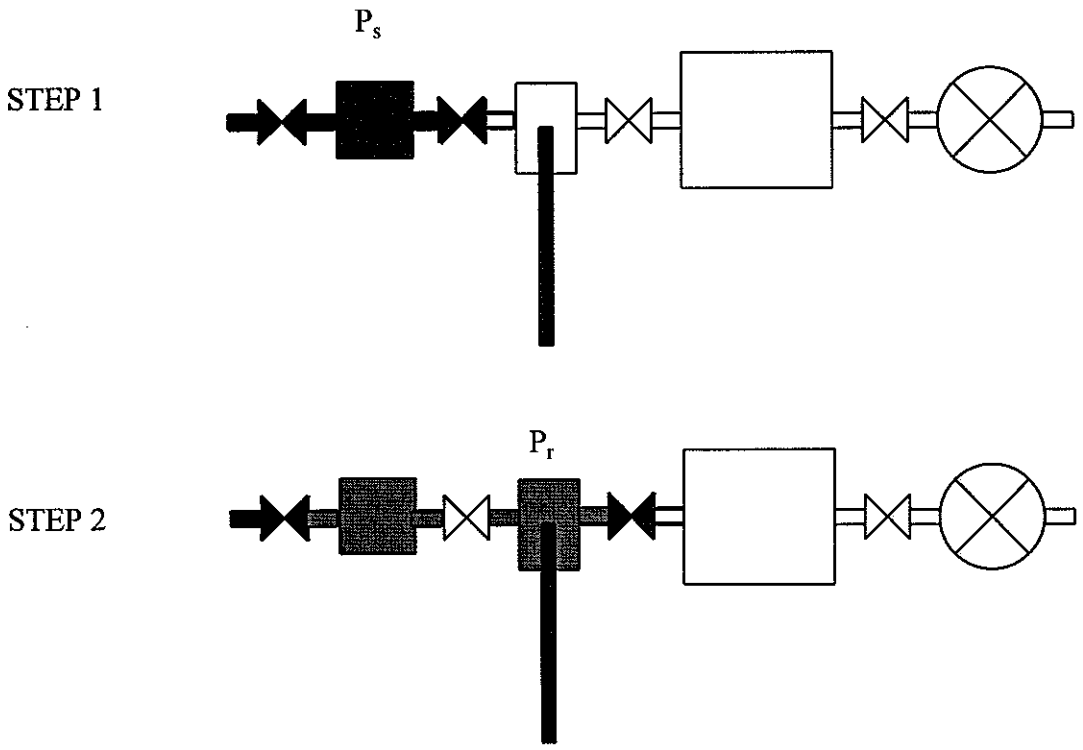
The fuel rod is driven into the apparatus. Airtightness is performed, and all vessels are pumped. The vacuum level is checked with a vacuum gauge.



2.2 Phase 1 : Measurement of the rod assembly volume

The rod assembly volume is measured before puncturing. It depends on the fuel rod geometry and must be determined for each fuel rod.

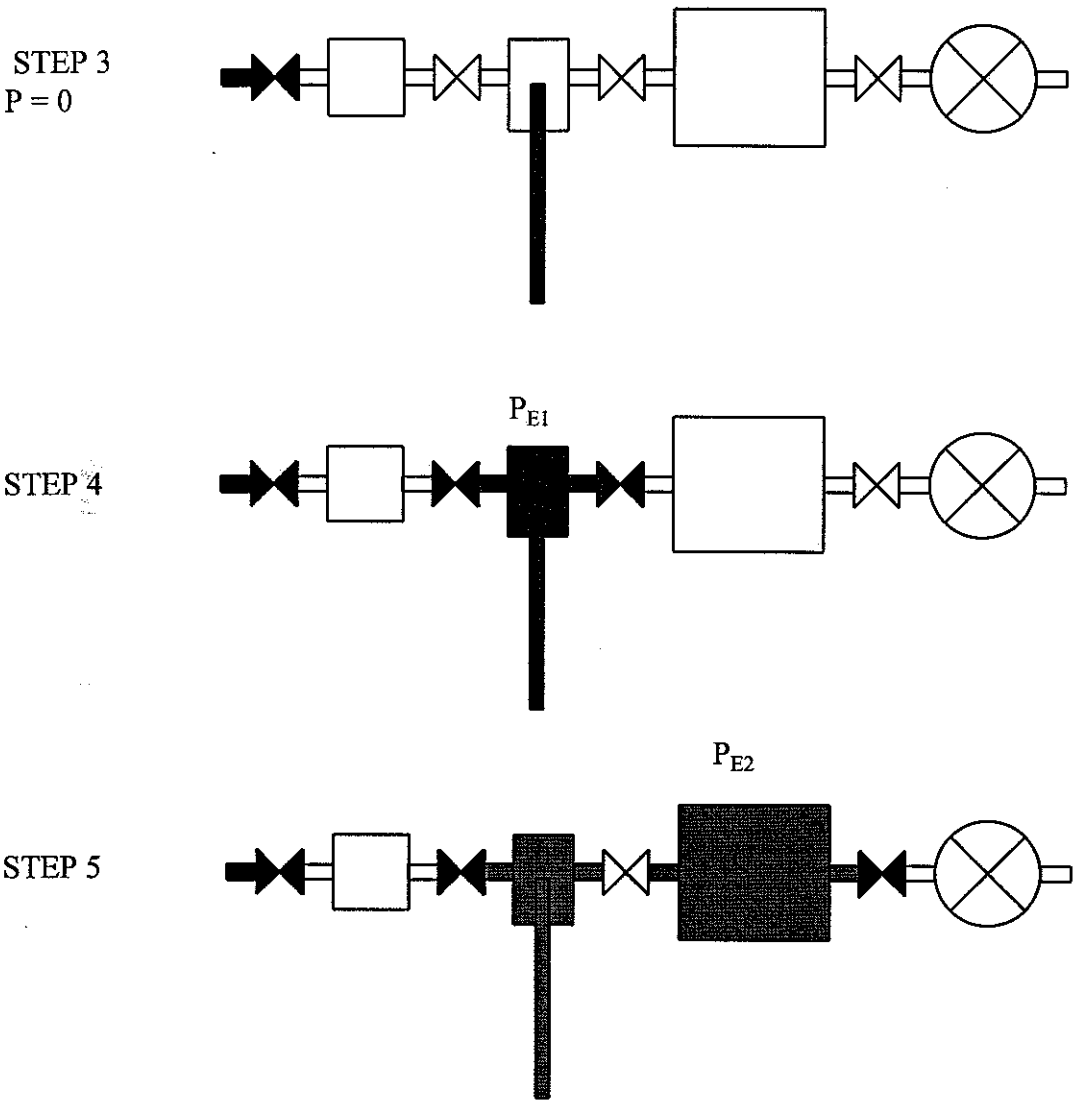
A known quantity of He gas is prepared when injecting it in the sampling assembly. The equilibrium is achieved (step 1), the pressure in the sampling assembly, P_s, is measured. Then this gas is expanded in the rod assembly. When the equilibrium is achieved (step 2), the pressure in the sampling assembly (equal to the pressure in the rod assembly), P_r, is measured.



Then V_r is calculated using the formula : $$V_r = V_s \frac{P_s - P_r}{P_r}$$

2.3 Phase 2 : Free volume measurement using the double expansion method

After phase 1, all vessels are pumped again (step 3). The rod assembly is isolated and fuel rod is punctured. When the equilibrium is obtained (step 4), the pressure of this first expansion, P_{E1}, is measured in the rod assembly. The expansion assembly is then isolated from the pump assembly, and the gas in the rod assembly is expanded in it. When the equilibrium is achieved (step 5), the pressure of this second expansion, P_{E2}, is measured in the rod and expansion assemblies.



Then V is calculated according to the following formulae derived from this double expansion method :

$$V.P_0 = P_{E1}(V + V_r) = P_{E2}(V + V_r + V_e)$$

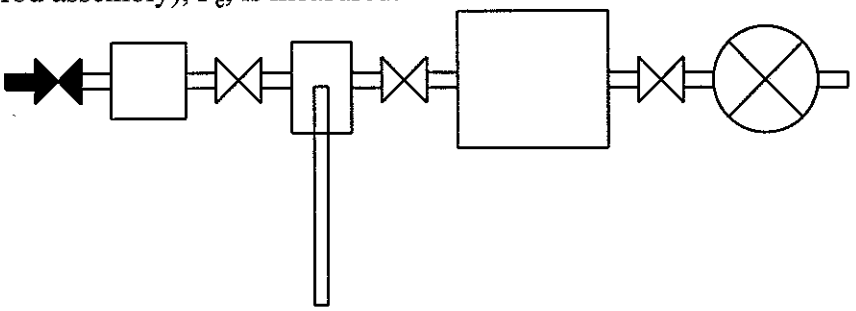
$$V = V_e \frac{P_{E2}}{P_{E1} - P_{E2}} - V_r$$

2.4 Phase 3 : Free volume measurement using the usual method

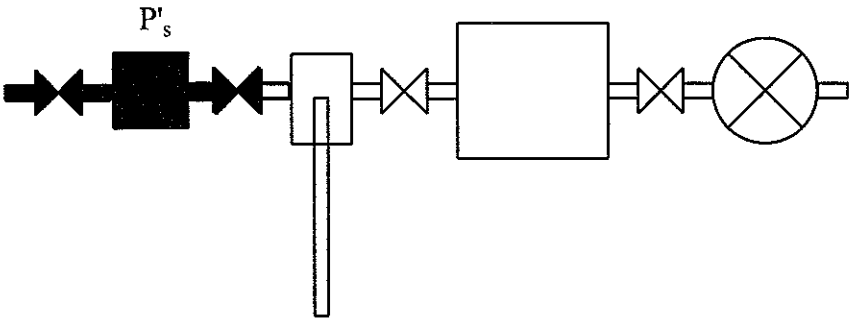
A fraction of the gas expanded from the fuel rod is sampled for chemical and isotopic analysis which are performed in a laboratory located at CEA Saclay. All vessels are pumped again (step 6). The free volume of the fuel rod is then determined using the same procedure as in phase 1.

A known quantity of He gas is prepared when injecting He in the sampling assembly. When the equilibrium is achieved (step 7), the pressure in the sampling assembly, P'_s, is measured. Then this gas is expanded in the rod assembly. When the equilibrium is achieved (step 8), the pressure in the sampling assembly (equal to the pressure in the rod assembly), P_e, is measured.

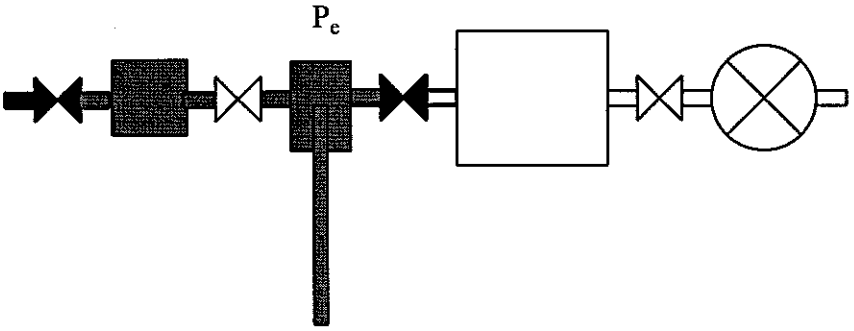
STEP 6
P = 0



STEP 7



STEP 8



Then V is calculated according to the following formulae derived from the usual method:

$$P'_s . V_s = P_e (V + V_r + V_s) \qquad or \qquad V = \frac{P'_s}{P_e} . V_s - V_s - V_r$$

P_0 is calculated with the same formula for both method (obviously the value of V depends on the method) :

$$P_0 . V = P_{E1} (V + V_r) \quad or \quad P_0 = P_{E1} (\frac{V_r}{V} + 1)$$

3. ACCURACY

The typical pressures values and sensors uncertainties are given in the following table :

quantity	value in MPa	uncertainty in 10^{-3} MPa
P_s and P'_s	0.24	0.25
P_r	0.17	0.25
P_{E1}	2.20	4.00
P_{E2}	0.22	0.25
P_e	0.12	0.25

With these values and absolute uncertainties listed above, the relative uncertainty of the free volume measurement is :

$\frac{\Delta V}{V} = 2.0\%$ *and* $\frac{\Delta P_0}{P_0} = 3.9\%$ for the usual method

$\frac{\Delta V}{V} = 1.4\%$ *and* $\frac{\Delta P_0}{P_0} = 3.0\%$ for the double expansion method

The accuracy for P_0 and V determination is not as good as these figures. A bias must be taken into account, because the volumes of the rod and the expansion assemblies are not known with an infinite precision. This bias is of the order of the precision given above.

The precision of the two methods are equivalent provided that the mathematical formulae can be applied safely. We will see in next chapter that the procedure used for measuring these pressures can have some influence.

4. FIRST EXPERIMENTAL RESULTS

Before its standard operation, the apparatus was tested with a PWR MOX fuel irradiated during 3 cycles in an EdF power plant. The procedure described above was applied. The obtained pressure measurements are presented here and the results are given.

During the phase 1, the pressure is measured in sampling assembly and its evolution is presented on figure 4.1.

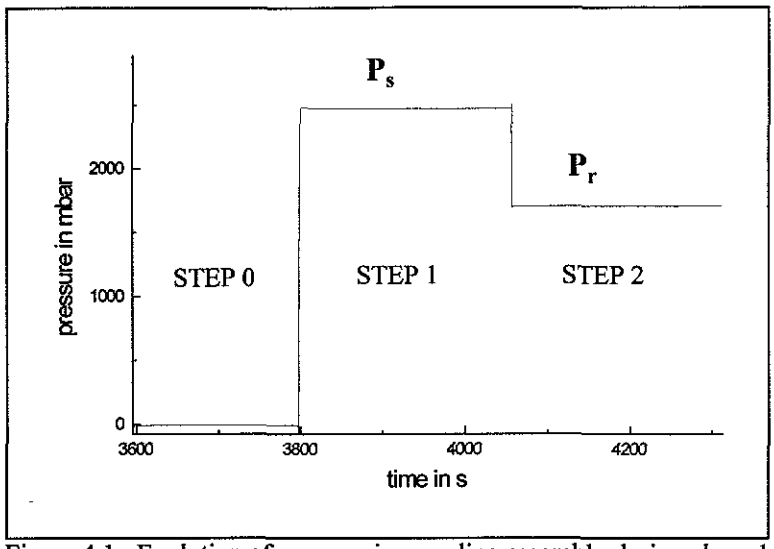


Figure 4.1 : Evolution of pressure in sampling assembly during phase 1

During the phase 2 (double expansion method), the pressure is measured in the rod assembly with a high pressure sensor during the first expansion. During the second expansion, the pressure is measured in the expansion assembly with a more accurate low pressure sensor. The pressure evolution for both sensors is given on figure 4.2.

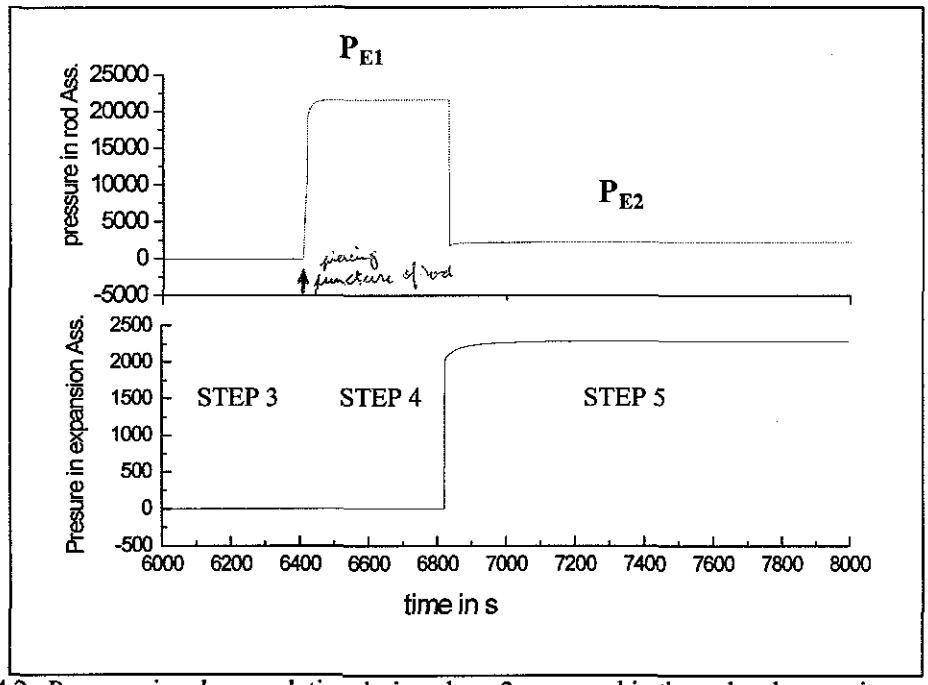


Figure 4.2 : Pressure, in mbar, evolution during phase 2 measured in the rod and expansion assemblies

It can be noticed on figure 4.2 that, after puncturing (step4), the pressure is not instantaneously stabilised as during the phase 1. For this reason, pressure measurements must be performed only when the pressure equilibrium is achieved. In step 5, for instance, the pressure recording of the tested MOX fuel lasted more than one hour, which gives a longer time line than the one presented in figure 4.2. Using formulae presented above, values of the free volume are calculated with the double expansion method for several values of the recording time, and will be presented on figure 4.4.

As in phase 1, the pressures in phase 3 (usual method) are measured in sampling assembly. The pressure evolution is given on figure 4.3

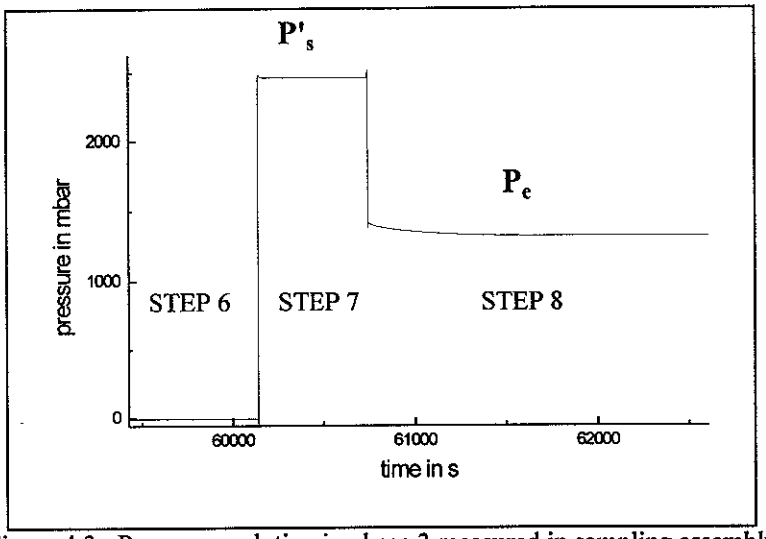


Figure 4.3 : Pressure evolution in phase 3 measured in sampling assembly

As in figure 4.2, the pressure evolution on figure 4.3 is not instantaneously stabilised. Again, the pressure recording lasted more than one hour in order to achieve the pressure equilibrium.

As told in the introduction, the accuracy of this usual method depends on the remaining gas in the fuel rod after pumping in step 6. Several measurements of the free volume of our tested MOX fuel were performed with different pumping times in order to estimate the influence of this parameter. The obtained values of the free volume are presented on figure 4.4 compared to these obtained with the double expansion method.

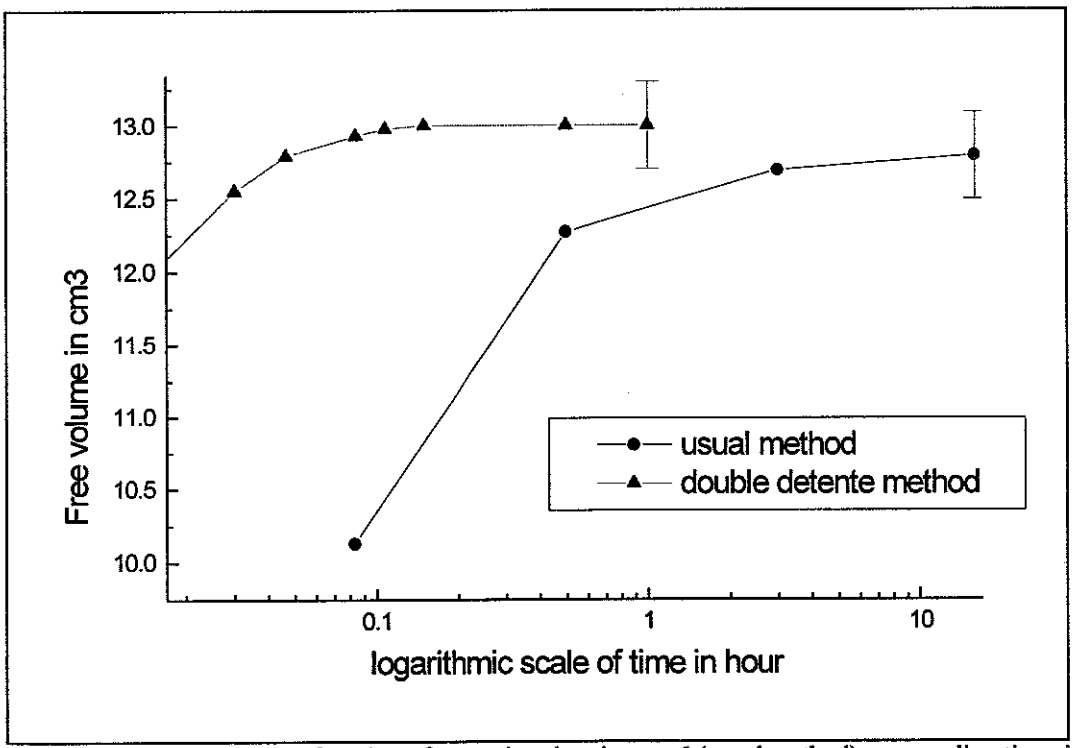


Figure 4.4 : Free volume as a function of pumping time in step 6 (usual method) or recording time in step 5 (double expansion method)

5. DISCUSSION

Figure 4.4 shows that the values calculated for the free volume of our tested MOX fuel tend to the same asymptotic value for both methods. However the double expansion method needs shorter time in step 5 to achieve pressure equilibrium, than the usual method needs to pump the fuel rod in step 6. This difference can be explained taking into account the gas flow within the fuel rod. A gas flow mathematical modelling will be presented in a further paper. In this paper, only simple calculations will be presented giving a comparison between the time needed in step 5 and in step 6 to make accurate measurements.

In step 5 (double expansion method), the gas, initially with a pressure equal to P_{E1}, is removed from the rod assembly to the expansion assembly and the equilibrium is achieved with a pressure equal to P_{E2}. In step 6 (usual method), the gas, initially with a pressure equal to P_{E2}, is removed from the rod assembly to the pumping system until a pressure nearly equal to 0 is achieved. In both steps, the fuel rod is emptied of its gas, but the initial pressure of the gas in the fuel rod is different.

In order to calculate the needed time to empty the fuel rod, we make the following assumptions:

- The continuous gas flow within the fuel rod can be determined with the following formula (see for example [3]) :

$F = A (P^2_{bottom} - P^2_{top})$

where F is the gas flow, P_{top} and P_{bottom} are the pressure in the top and bottom of the fuel rod respectively, and A is a constant depending on the fuel rod hydraulic diameter and the gas properties. P_{top} is less than P_{bottom}, and can be disregarded. P_{bottom} is considered to be equal to P_i the initial pressure in the fuel rod. With these approximations the formula can be written:

$F \approx A.P_i^2$

- The quantity of gas in the fuel rod is initially equal to :

$Q = V.P_i$

- The time needed to empty the fuel rod, t, is then equal to:

$t = Q/F$

Using these formulae, the needed times to empty the fuel rod in step 5 and 6, $t_{double\ expansion}$ and t_{usual} respectively, times can be compared :

$$\frac{t_{usual}}{t_{double\ expansion}} \approx \frac{P_{E2}}{P_{E1}} \approx 10$$

According to this very simplified calculation, $t_{double\ expansion}$ is one order of magnitude shorter than t_{usual}. This semi-quantitative interpretation agrees well with our experimental results (figure 4.4). Simply speaking, the double expansion method takes advantage of the fact that it is easier to empty the fuel rod of its gas when it is under high pressure.

CONCLUSION

The new apparatus built in the CEA hot lab STAR, in Cadarache centre, with two possible determinations of free volume brought out results showing that free volume determination depends on experimental procedure.

With the usual method, pumping time is a key parameter : it must be long enough to warrant that fuel rod is actually free of residual gas. Unfortunately there is no measurements which allows to verify that fuel rod is actually empty. It is also difficult to estimate how long pumping time must be. It depends indeed on the fuel rod hydraulic diameter, which varies with burn up and which is not easily determined in hot labs environment.

The double expansion method has two mains advantages. First it needs shorter time for pressure stabilisation and reduces experimentation time. Second, the stabilisation of pressure is a proof that equilibrium is reached and that mathematical formulae can be used safely.

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