Development and manufacturing of special fission chambers for in-core measurement requirements in nuclear reactors

B. Geslot, S. Bréaud, C. Jammes, P. Filliatre, J-F. Villard, F. Berhouet

***Abstract*—The Dosimetry Command control and Instrumenta-tion Laboratory (LDCI) at CEA/Cadarache is specialized in the development, design and manufacturing of miniature fission chambers (from 8 mm down to 1.5 mm in diameter). LDCI fission chambers workshop specificity is its capacity to manufacture and distribute special fission chambers with fissile deposits other than U235 (typically Pu242, Np237, U238, Th232). We are also able to define the characteristics of the detector for any in-core measurement requirements: sensor geometry, fissile deposit material and mass, filling gas composition and pressure, operating mode (pulse, current or Campbelling) with associated cable and electronics. The fission chamber design relies on numerical simulation and modeling tools developed by the LDCI. One of our present activities in fission chamber applications is to develop a fast neutron flux instrumentation using Campbelling mode dedicated to measurements in material testing reactors.**

***Index Terms*—Neutron detectors, Fission reactors**

I. Introduction

A long-standing activity of the Dosimetry Command control and Instrumentation Laboratory (LDCI) at CEA Cadarache is to develop and manufacture miniature fission chambers. Those neutron detectors are used to locally characterize the in-core neutron flux of nuclear research reactors. Fission chambers are manufactured at the CHICADE facility (Cadarache).

Since in-core measurements require small detectors, LDCI Fission Chamber Workshop (FCW) makes it possible to manufacture miniature fission chamber (from 8mm down to 3mm diameter) and more recently sub-miniature fission chambers (SMFC) with a 1.5mm diameter.

Several detector geometries are available but FCW detectors are generally based on a cylindrical geometry: fission chambers are composed of two concentric electrodes. The fissile deposit lies on either of the electrodes.

Most fission chambers use a U235 fissile deposit to interact with neutrons. Since U235 is mainly sensitive to thermal neutrons, they are thus used to monitor the in-core thermal flux, which is generally the largest part of the flux (around 70% in thermal MTR).

However, there are reactor applications that require a detector sensitive to fast neutrons. That comes from the fact the fast neutron flux is responsible for most of the material damages. In critical facilities, one is also interested in locally characterizing the neutron flux by measuring the fast flux proportion.

LDCI FCW specificity is its capacity to manufacture and distribute so-called "special fission chambers" with fissile deposits other than U235 (typically Pu242, Np237, U238, Th232). Depending on the application (flux intensity, neutron spectrum, geometry…), we are able to design a specific detector (fissile isotope, sensitivity, gas composition and pressure) that meets the measurement requirements.

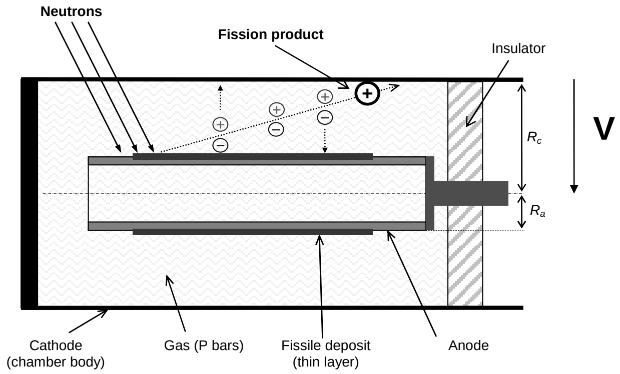

Fig. 1. Simplified drawing of a fission chamber (cylindrical geometry)

II. Fission chamber principles

A. Detector details

Fission chambers are simple ionization chambers with a fissile material deposited on one of the electrodes (Fig. 1). When placed in a neutron field, fissile atoms react with neutrons. Several kinds of reaction occur in the fissile deposit, but the main reaction is the fission reaction that produces two high energy fission products per fission (around 165MeV in total).

One of them finds a way out of the fissile deposit and flies through the electrode gap. Numerous ion-electron pairs are

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created in the chamber filling gas. A sufficiently high voltage between the electrodes allows collecting those charges. The detector signal consists in the resulting current measured at the output of the detector.

Let N be the number of atoms in the deposit and $\bar{\sigma}$ the condensed fission cross section of the fissile isotope (NB: $\bar{\sigma}$ depends on the neutron spectrum). The fission rate R is related to the flux Φ through the following equation:

$$R = N \cdot \bar{\sigma} \cdot \Phi .$$

The measured signal I (for instance the mean output current) is proportional to the fission rate (at least in first order). However, signal is also a complex function of several parameters, among which we find:

- chamber geometry (impacts the electrode gap),
- gas pressure P,
- gas composition (impacts the electrons and ions mobility),
- polarization voltage V.

Finally, one can introduce a calibration coefficient K_d (only related to the ionization chamber characteristics) as follows:

$$I = K_d (V, P, R_c, R_a, ...) \times R$$

Fission chamber sensitivity S is simply the ratio between signal and flux:

$$S = K_d \cdot N \cdot \sigma$$

Being able to calculate fission chamber sensitivity *a priori* is of great interest in order to precisely adapt fission chambers to measurement requirements. LDCI laboratory currently develops modeling tools in order to improve detector knowledge [1].

B. *Measurements operating modes*

It is well known that a fission chamber produces a current pulse every time a neutron induces a fission reaction in the fissile deposit. One a can distinguish two cases depending on the fission rate.

At low fission rates (i.e. low fluxes or detector sensitivity), pulses are separate from each other. The easiest way to measure a quantity proportional to the fission rate (and to the flux) is to discriminate the current pulse from the background noise and to monitor the pulse counting rate. This operating mode is called "pulse mode".

At higher fission rates (i.e. high fluxes or high detector sensitivity), individual pulses cannot be separated. One has to measure the characteristics of the overall current. The Campbell theorem states that the first two statistical moments of current (average and variance) are proportional to fission rate (see reference [2]). When measuring the average current, one uses the so-called "current mode". When measuring the current variance, one uses the "Mean Square Voltage (MSV) mode" or "Campbelling mode". Figure 2 shows a sketch of standard electronics used in current mode.

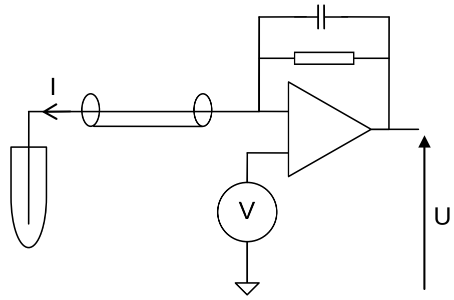

Fig. 2. Simplified electronics scheme for measuring a tension U proportional to the current I delivered by a fission chamber polarized by a voltage V

III. Fission chamber manufacturing

A. *Mechanical pieces*

Most of the mechanical parts that constitute LDCI fission chambers are tubes or machined metal parts provided by CEA contractors (figure 3). Those parts are generally made of stainless steel or titanium. For high temperature applications, chamber parts are made of nickel, inconel (nickel-chromium-based alloy) and aluminum.

We also use electric insulators made of alumina during the assembly process.

Fig. 3 shows the drawing of a typical fission chamber (4 mm diameter). Two very important parts are the deposit electrode that houses the fissile material and the insulator tube that maintains the voltage between the electrodes.

Before assembling the detector, each mechanical part is cleaned and degreased (using ultrasounds). Then, parts are degassed under vacuum with monitored temperature (between 350°C and 600°C depending on the application). In order to be ready to house the fissile deposit, the deposit electrode undergoes a surface treatment (sandblasting).

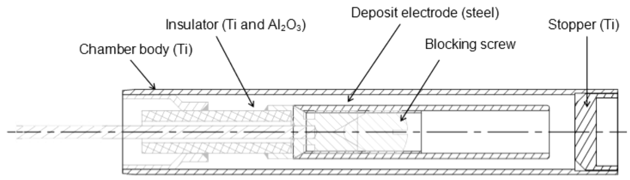

Fig. 3. Fission chamber drawing (4 mm diameter)

B. *Fissile material deposition*

Most fissile isotopes used in fissile deposit by LDCI FCW are listed in Table 1. Fissile material mass depends on the fission chamber type (from a few µg up to a few mg). Maximum surface mass is around 2 mg/cm^2, that corresponds to 10 mg maximum for 8 mm diameter fission chambers.

In most cases, fissile material lots do not contain 100% wanted isotope. Isotopic composition must be taken into account when calculating deposit activity, as it is shown in Table 1.

As far as it concerns the fissile deposit sensitivity to neutrons, one has to pay attention to impurities that may have a significant contribution to the signal. That effect causes a bias in the measurement.

TABLE I
FISSILE ISOTOPES USED BY CEA FCW AND RELATED ACTIVITIES

Iso.	Specific activity (Bq/g)	Activity for 1mg (principle isotope)	Activity for 1mg (with impurities)
Th232	$4.06\ 10^{3}$	$4.06\ 10^{0}$	$4.06\ 10^{0}$
U nat.	-	-	$1.39\ 10^{1}$
U233	$3.57\ 10^{8}$	$3.57\ 10^{5}$	$5.95\ 10^{5}$
U234	$2.30\ 10^{8}$	$2.30\ 10^{5}$	$2.30\ 10^{5}$
U235	$8.00\ 10^{4}$	$8.00\ 10^{1}$	$2.23\ 10^{2}$
U238	$1.24\ 10^{4}$	$1.24\ 10^{1}$	$1.31\ 10^{1}$
Np237	$2.61\ 10^{7}$	$2.61\ 10^{4}$	$2.66\ 10^{4}$
Pu238	$6.33\ 10^{11}$	$6.33\ 10^{8}$	$6.34\ 10^{8}$
Pu239	$2.30\ 10^{9}$	$2.30\ 10^{6}$	$2.52\ 10^{6}$
Pu240	$8.43\ 10^{9}$	$8.43\ 10^{6}$	$8.53\ 10^{6}$
Pu232	$1.45\ 10^{8}$	$1.45\ 10^{5}$	$8.32\ 10^{5}$
Am241	$1.27\ 10^{11}$	$1.27\ 10^{8}$	$1.27\ 10^{8}$

Fissile material is deposited on the electrode by means of electrolysis. A special hand-glove box is dedicated to that step. Each isotope is initially contained in a highly concentrated liquid solution. The electrolyte base solution is made of nitric acid and ammonium oxalate.

The electrolysis is achieved using a low current maintained during a long time so that there is very little fissile material left in the solution.

A typical fissile deposit is shown on Fig. 4 (picture taken using a scanning electron microscope, see ref. [6]). One can see the deposit is not perfectly flat but small material clusters can be distinguished. The fissile material constitutes most of the deposit (in dark gray) but a few white clusters can be seen. It is thought those clusters are made of platinum that has deposited during the electrolysis process.

The parceling of the deposit is certainly due to the heating phase that the deposit undergoes after the electrodepositing process.

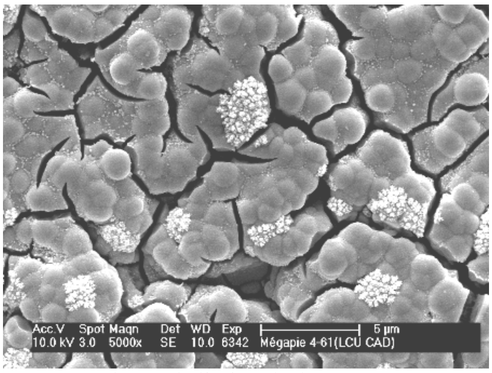

Fig. 4. Fissile deposit view (SEM)

C. Detector assembly and filling gas

The process used to assemble chambers parts depends on the detector geometry. For the largest detectors (4 mm and 8 mm diameter), we use tungsten inert gas (TIG) welding. For smaller detectors, laser welding is used for better precision.

TIG welding is achieved under stabilized argon atmosphere (a few bars). The welding airtight box is placed in a dedicated hand-glove box. Welding intensity is around a few amps.

Laser welding (figure 5) is used because of its greater precision on small fission chambers (3mm and 1.5mm diameter). The laser is remotely controlled and a movie camera allows the operator to monitor the process.

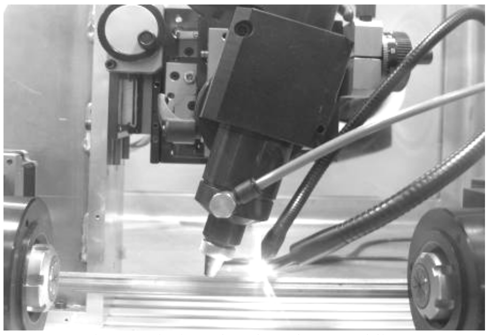

Fig. 5. Fission chambers laser welding

D. Post manufacturing tests

A simple way to test an ionization chamber and its operating cable is to measure the insulation resistance. Good functioning requires an insulation resistance of at least 10^{12} ohms (under 150 V). A weak insulation resistance induces a leak current in the detector or cable that prevents from measuring.

The good quality of the welding is checked using a helium leak detector. In the case of the last welding (that closes the chamber), we prefer to measure the insulation resistance while the detector is under alcohol.

Finally, the good operating of the detector and cable is tested under X rays irradiation (energies around 100 keV). The measured signal (a few nA) is a due to the gas ionization: it could be used to compare the ionization chamber sensitivities.

Figures 6 and 7 show FCW fission chambers with various diameters (from 1.5mm to 8mm). 1.5mm diameter fission chambers have the specificity to be delivered with an integrated cable to avoid connection problems.

IV. MEASUREMENTS REQUIREMENTS

A. Fission chamber use in zero power reactors

Neutronic measurements in zero power reactors generally require two kinds of fission chambers:

- Sensitive fission chambers placed in the core or in the reflector and generally used to monitor the reactor operation during the measurements.
- Small fission chambers placed in the core, often between fuel elements, used to characterize the flux distribution in the core.

The flux characterization may include flux traverses (radial and axial) but also spectrum indices obtained with different isotope measurements.

Fig. 6. CEA fission chambers (4mm and 8mm diameter)

More rarely, specific measurements are carried out using very sensitive detectors in order to estimate neutronic integral parameters of the core (delayed neutron fraction and generation time).

In zero power reactors, flux levels are between 10^7 and 10^9 n/cm^2.s. Fission chambers are operated in pulse mode, in which the evolution is obtained from the observed counting rate in time.

Precise measurement of the counting rate is obtained using pulse height analysis (PHA). That measurement method (that uses a charge pre-amplifier) permits to precisely discriminates neutron pulses from pulses induced by other particles (alpha or gamma). This way, one can get a fixed signal to noise ratio.

B. Fission chamber use in MTR

In material testing reactors (MTR), fission chambers are used to monitor the flux on-line during an irradiation measurement. Given that the most important parameter is the thermal fluence, most of the time one uses thermal detector such as uranium-235 fission chambers or self-powered neutron detectors (SPND).

However, in some experiments, it is important to measure the fast neutron flux, for instance for fusion dedicated material studies (as most material damage is induced by fast neutrons). In that case, it is possible to use LDCI fission chambers with fissile deposit such as Pu242 or U238.

The problem of measuring the fast neutron flux in presence of a strong thermal flux was recently addressed by LDCI [2-3]. Proposed solution is based on two detectors: one Pu242 fission chamber sensitive to fast neutrons and one detector mainly sensitive to thermal neutron. The second measurement is used to correct the first one from the thermal component induced by impurities in the Pu242 deposit.

Because of the high flux in MTR (up to nearly 10^{15} n/cm^2.s), detectors are operated in current mode. The Campbelling mode is also a promising operating mode: systems using tha mode are under development. There is also a strong gamma field due to nuclear activation in reactor structure. When using the fission chamber current mode, which is the most convenient mode to operate in, one is compelled to correct the measurement from the signal induced by the gamma flux. That correction can be as great as 50% of the signal. Correction can be made as post processing or during measurement using a second detector without fissile deposit but the same design [6].

It has been recently shown [3-4] that the Campbelling mode is able to dramatically reduce gamma contribution. The reason is that the signal in Campbelling mode is proportional to the square of the charge deposited in the gas by an ionizing particle.

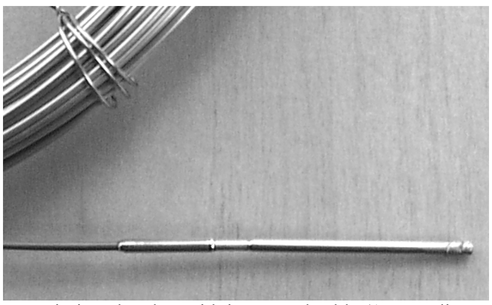

Fig. 7. Fission chamber with integrated cable (1.5mm diameter)

V. CONCLUSION

In this paper, the manufacturing process used by the LDCI FCW to manufacture miniature fission chambers is described. We emphasized the specificity of our workshop that is to manufacture fission chambers with fissile deposit other than U235.

We are able to adapt the detector design to meet the measurement requirements by modeling the evolution of fissile deposit as well as the ionization chamber response. Nowadays, LDCI is developing simulation tools in order to improve detector design.

We are also developing acquisition systems to be used with fission chambers in various operating modes. For instance, LDCI is involved in the qualification of a data acquisition system using Campbelling mode. The Fast Neutron Detector System (FNDS) will be used to measure on-line the fast neutron flux in MTR. FNDS will be soon qualified with miniature Pu42 fission chambers (3mm diameter) in SCK•CEN BR2 reactor [5].

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