JHR PROJECT- EU JHOP 2040 GAMMA DOSE TOLERANCE TESTS FOR IRRADIATION LOOP INSTRUMENTATION

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ABSTRACT

The Jules Horowitz Reactor (JHR) is under construction in the south of France at the CEA Cadarache. The JHR is a modern facility, MTR type (Material Testing Reactor), taking into account the last safety and regulation requirements. The JHR will meet the needs of operators in terms of materials and fuel irradiations for current Nuclear reactors (Gen.2, 3) and future reactor generations (Gen. IV, fusion support).
It will also produce radioelements (mainly Mo99) for medical applications.
This project is performed and will be operated within the framework of a consortium gathering countries or partners institutions including France (CEA, EDF, FRAMATOME, TECHNICATOME), European Union (JRCs) as well as other contributing countries (Belgium, Spain, Finland, Sweden, Czech Republic, Israel, India, Japan, UK, China).
In this context, a European CSA program is running in the period 2020-2023 within JHR EU partners. The tests presented in this paper concern this program.

In the process of development of the irradiation devices fleet for the JHR reactor, technological qualification tests are necessary. They contribute to validate, from the experimental point of view, the proposed technological concepts. They allow also de-risking the studied designs and allowing verifying the associated experimental performances before manufacturing the final components.
This paper proposed concerns irradiation devices fleet and “ADELINE type” components. Typically, this type of device will be devoted to perform in the JHR power ramps tests on an irradiated fuel rod.
After a reminder of the general context of the JHR project, the main characteristics of the reactor and the irradiation devices, a focus is made on the preliminary qualifications activities regarding critical components identified for “ADELINE type” device.
In this context, gamma tolerance tests on pressure sensors are presented.
The goal of these tests were to verify the behaviour of the sensors regarding gamma irradiation in normal & off normal experimental conditions (4 kGy).
Then, the sensors have been tested at higher gamma up to 70 kGy in order to verify theirs robustness in industrial conditions.
These tests have been performed in 2021 in collaboration with CVR-Rez institute, located in Czech Republic.

1. INTRODUCTION

The Jules Horowitz Reactor (JHR) is under construction in the south of France at the CEA Cadarache. In the process of the development of the irradiation device fleet for the JHR reactor operation, technological qualification tests are identified.
These tests contribute to validate the concept proposed during the design phase.
It allow also checking the associated experimental performances.
This is in this context and for the "ADELINE type" fuel irradiation device that this paper is proposed.
It concerns gamma tolerance tests on pressure sensors located in the Thermal Hydraulic containment of the experimental ADELINE loop. These tests have been performed in 2021, in collaboration with Research Centre Rez (CVR), located in Czech Republic.

2. CONTEXT REMINDER

2.1 JHR Facility

The Jules Horowitz Reactor, which is currently under construction at the CEA Cadarache center (Bouches-du-Rhone department, France), is a material testing reactor (MTR). It will be used to perform irradiation tests on Fuel and Material samples as part of support Programmes for current nuclear power reactors (Gen II and III) and future reactors (Gen IV and fusion). This reactor will also be used to produce radioelements (mainly Mo-99) for medical purposes and will meet 50% of the European demand in this field.

Figure 1a: JHR support building. v2019, July

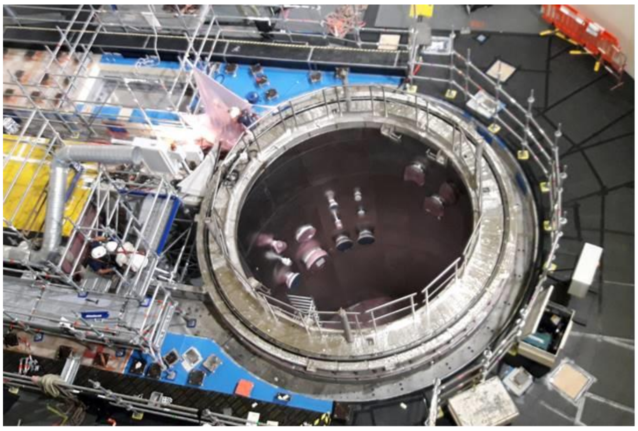


Figure 1b: JHR reactor pool overview. v2019, sept.

2.2 Main Characteristics Of The Reactor

The main characteristics of the Jules Horowitz reactor are recalled below [R1]:

- the compact core is designed to generate a nominal power up to 100 MWth,
- it is cylindrical in shape, with a diameter of 60 cm and a height of 60 cm,
- the reactor is immersed under 9.3 m of water (level with the mid-height plane) in a pool that is 12 m deep,
- the core is under-moderated in order to generate strong fast neutron fluxes, i.e. up to $5e^{14}$ n.cm^{-2}.s^{-1}, E > 1MeV,
- the primary system is closed and slightly pressurised (12 bar upstream of the core),

- the cooling water in the core flows upwards at a velocity of about 10 m/s,
- gamma heating in the core is about 15 to 20 W/g (maximum local value),
- the beryllium reflector is 30 cm thick and surrounds the core vessel. Its role is to thermalize the neutrons produced in the core,
- the thermal neutron flux in the reflector is $3e^{14}$ $n.cm^{-2}.s^{-1}$.

Ten experimental locations will be available in the core and another ten in the reflector, including six on the displacement systems, which are designed to modify the distance between the samples and the core in order to control the nuclear power in the fuel sample. After the divergence phase of the reactor, the start-up phase of the experimental equipment's is planned over a one-trial period spanning 12 to 18 months.
Once this stage is reached, the experimental loops will be operational and ready to meet the needs of future customers.

2.3 The JHR Irradiation Loop for Fuel Power Ramps Tests.

2.3.1 Main Features

An experimental irradiation loop dedicated to rod irradiation functioning under LWR conditions in under detailed study (cf. fig.2). This loop is called ADELINE [R1, R2].
This fuel irradiation loop is composed of an in-core part located in the reactor pool and of another part located in the operation zone of the experiments (BUR, CEDE).
The in-core part includes the irradiation device equipped with a rod, the underwater lines and the fluid & electrical connections through the experimental penetrations of the pool.
The other part is made up of the fluid circuit, a tight bunker and connection of the circuit with the utilities of the JHR facility.
The fluid circuit is equipped with pressurization system and circulating pumps, making it possible to obtain the circulation of water-cooling towards the device and to reach the required thermal-hydraulic conditions at the bottom of the test channel (P=155 bar, T=270°C, Q=200 to 250g/s).
The experimental loop under study also takes into account the feedback of this kind of loop like the ISABELLE irradiation loop, which was used on the OSIRIS irradiation reactor located in SACLAY (FRANCE) and which was operated up to 2015.

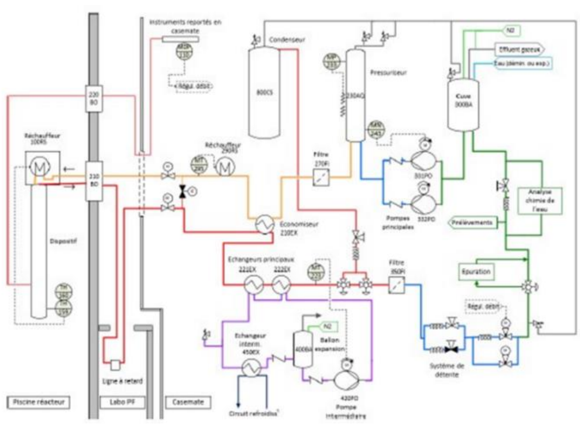
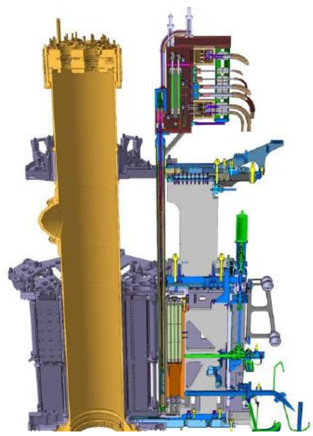
	

Figure 2a: simplified drawing of a fuel irradiation loop ("ADELINE type" device , TH loop, v 2021)	Figure 2b: overview of the "ADELINE type" device in-pile part in the JHR core environment.

2.3.2 Expected Performances of the Loop

The experimental rod is composed of a UO_2 type or MOx, irradiated or not.
The standard profile of power during the test is described hereafter:

- Conditioning phase with low power (100 W.cm^{-1}) ranging from a few hours to a few days,
- Power ramp test with kinetics going up to 700 W.cm^{-1}.min^{-1},
- Power aimed at the high level of 620 W.cm^{-1}+/-10W.cm^{-1} for one maximum duration of 24 hours,
- Withdrawal of the device according to the power decrease scenario.

The physical parameters around the rod correspond to the following PWR conditions: P=155 bar, T=320°C with a fluid flow of Q=0.2 to 0.25 kg/s and P=73 bar, T=280°C for BWR conditions.
Regarding the displacement system (SAD), it can move to or from the core tank. It allows implementing linear power variations simply and quickly on the sample and reaching representative power level and fission products inventory during conditioning phase and before a soliciting test.

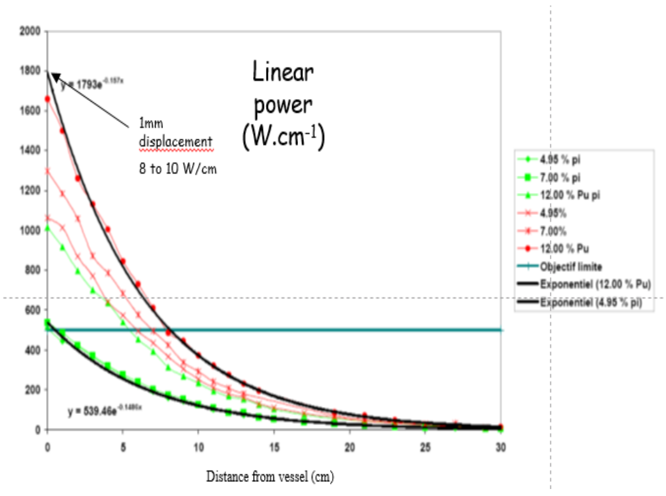


Figure 3a: Example of power evolution versus SAD displacement and fuel enrichment (analytical calculations).

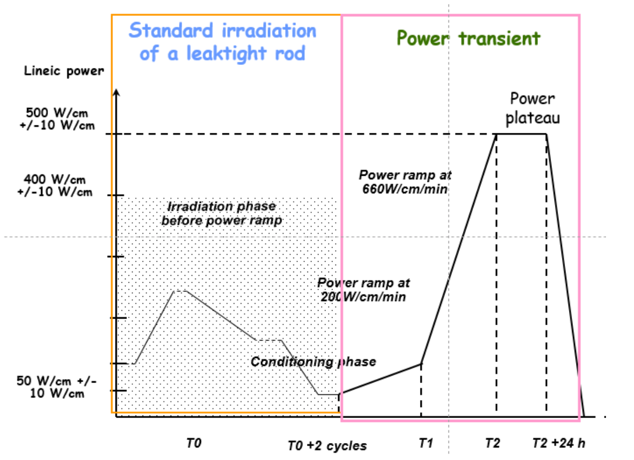


Figure 3b : Typical experimental scenario of a fuel power ramp test.

Such a concept is convenient for operation (easy to handle, even during the operating cycle of the core) and for safety, the backward position and the off normal conditions of the device are not directly coupled to the core operations.

3. IRRADIATION TEST FRAMEWORK

3.1 Introduction

The JHR project is performed and will be operated within the framework of a consortium gathering countries or partners institutions including France (CEA, EDF, FRAMATOME, TECHNICATOME), European Union (JRCs) as well as other contributing countries (Belgium, Spain, Finland, Sweden, Czech Republic, Israel, India, Japan, UK, China).
In this context, a European CSA program is running in the period 2020-2023 within JHR EU partners. The tests presented in this paper concern this program.

3.2 Input Data

The sensors selected for the irradiation resistance tests are industrial pressure sensors. Two types of sensors have been identified:

- The analog (type Y) P and delta P sensors which will be used as test sensors during the tests (and later on the JHR) thanks to their efficiency in terms of resistance to irradiation (object of the tests);
- The digital sensors (type K) P and dP which will be used as reference sensors due to their high measurement accuracy. However, they show a low resistance to irradiation (50Gy).

The following table lists the main characteristics of the sensors as well as the test conditions:

sensor location	**Fluid Process Pressure P In the circuit (Cubicle)**	
sensor type	*Relative pressure P sensor analogical type Y*	*relative pressure P sensor numerical type K*
function	*test sensor*	*reference sensor*
nominal working pressure	*155 bar*	
maximal working pressure	*185 bar*	
sensor range	*0 - 250 bar*	
Acceptable dose rate	*To define during the test*	*50 Gy*[1]

sensor location	**Delta P Flowmeter (VCone) Test Device**	
sensor type	*Differential Pressure dP sensor analogical type Y*	*CVR calibration pressure sensor*
function	*test sensor*	*reference sensor*
nominal working pressure	*0 - 640 mbar*	
sensor range	*0 - 700 mbar*	
Acceptable dose rate	*To define during the test*	*Not precised*

Note: during the planned tests, the identified “test sensor” will be irradiated. The so-called “reference sensor” will be used only for the purpose of recovering a very precise measurement of the pressure in order to be able to evaluate the measurement drifts of the test sensor as well as possible.

3.3 Tests Grid Proposal

The purpose of experimental program is to test a component under specific conditions in order to characterize its resistance over time and its ability to continuously perform its

[1] Pressure sensors supplier information

functions & performance, etc. In this case, the tests aim to qualify certain types of pressure sensors in the “ADELINE type” loop withstand irradiation in degraded situations.
By degraded situation is meant the consequence of rupture of the experimental rod embedded in the “ADELINE type” experimental device, which leads to a transfer of radionuclides from the rod to the coolant.
The dose absorbed by the sensors during a rod rupture has be estimated around 0.43 Gy/h. Even if this value is considered as an envelope, it will still be used to determine an absorbed dose value over a year. The resulting value is equivalent to 3.77 kGy.
The test value has been fixed at 4 kGy.

3.4 Post Test Controls

In order to verify the behavior of the sensors after irradiation, two controls benches were carried out. One for the relative pressure sensor control and a second for the differential sensor.

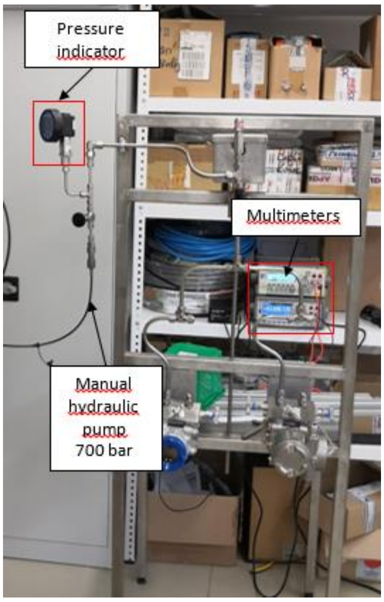


Figure 4a: Pressure sensors control bench

(relative Pressure)

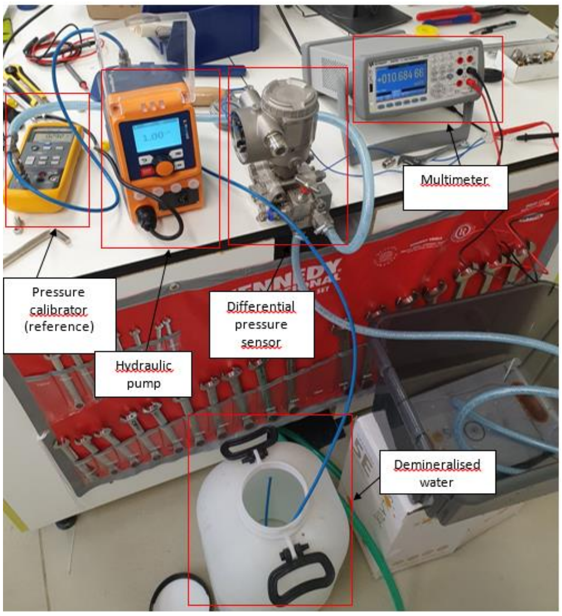


Figure 4b : Pressure sensors control bench

(differential Pressure)

3.5 The CVR Irradiation Facility

3.5.1 Presentation

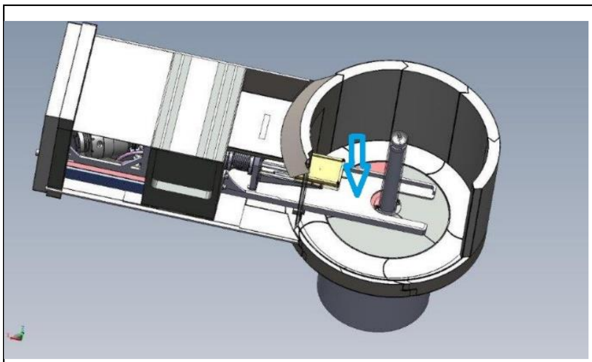
To irradiate the pressure sensors by gamma rays, a laboratory with the Gamma Irradiation Chamber (see Fig.5) at the Research Centre Rez was used. The laboratory is a unique facility equipped with the Co-60 source of the current activity 96 TBq.
It was built under the SUSEN project (Sustainable Energy) and put into operation in 2017. The main purpose of the laboratory is to provide a background for research and testing in the field of nuclear energy, industry, medicine and other services and it is used to irradiate the components, materials, and samples at normal and higher temperatures for heat radiation and aging so as to simulate the operation conditions of the nuclear power plants. The dimensions of the irradiation chamber are 100 cm circle diameter and 40 cm of height, so it was possible to place both sensors inside.

Figure 5: The laboratory

with the Gamma Irradiation Chamber

3.5.2 Dosimetry Process Description

In order to characterise with accuracy the gamma dose levels in the irradiation chamber, a dosimetry process with alanine detectors is performed. The sensor is placed close to the gamma source.
At first, the gamma dose rate was measured using the alanine detectors.
The detectors were placed on the body of the electronic part of the sensor.
There were placed six detectors symmetrically on both sides (left and right) of the sensor (see Fig.6). The detectors were fixed on the sensor using a tape.



schema (closed chamber)	a real position on the table (open chamber)

Figure 6: sensor location in the irradiation chamber

The evaluation of the measurement was provided by UJV Rez.
The uncertainty of the measurement using the alanine detectors is ca. 3%.
Based on measurement, the conditions for sensors irradiation were specified. The sensors were placed in the irradiation chamber symmetrically to reach identical dose rate on both sensors.

The example of sensor placed in the chamber is in Fig.7.

Figure 7: The tested sensors equipped with alanine detectors

3.6 Irradiation Phase

The sensors irradiation tests have been performed in CVR. 2021, week 31.
These tests can be divided into two parts:

The first part of the tests consists in evaluating any deterioration in the signal of the sensor tested in the range of the dose absorbed by the instruments in the ADELINE type" containment".
Note: the value of the dose rate of 4 kGy/year is explained in §3.3.
For the first part of the tests, three irradiation stages have been carried out at 2,4 and 8 kGy according to the scenario described below.
It is considered that the signal is deteriorated if the measurement inaccuracy exceeds 2%[2].
The measuring elements of a pressure sensor are located in the electronic box in the same box of the sensor. Therefore, the sensors will be positioned so that the electronic box receives the greatest dose rate value (this varies greatly depending on the distance).

The scenario adopted for the first part of the tests is as follows:

- Insertion of the test pressure sensor alone into the irradiation chamber;
- End of irradiation step, range [0-8 kGy, 2 steps at 2 kGy and 1 step at 4 kGy];
- Recovery of the sensor and installation on the test circuit;
- Inflating the lines of the control bench according to the operating pressure identified for the tested sensor, pressurization time [10 min], return to P_atm;
- Recording of any drifts between P_ref and P_test;
- Reintegration into the irradiation chamber.

The second part of the tests consist of irradiating the test sensor until an absorbed dose value up to 70kGy.
This will make it possible to go beyond the above-mentioned thresholds and to qualify the sensor for sensors industrials requirements.
For the second part of the tests, four irradiation stages will be carried out at 10, 30, 50 and 70 kGy according to the same scenario as for the first part.

3.7 Results Obtained

The graph hereafter presents the gamma dose level evolution versus time regarding the pressure sensors irradiation.

[2] Sensors supplier information

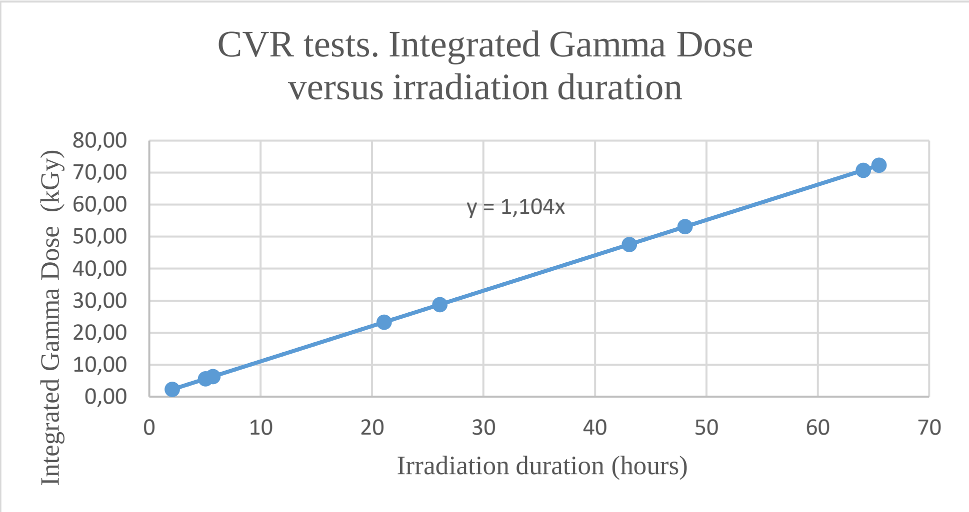


Figure 8: Gamma dose rate evolution (kGy) versus irradiation duration (h)

3.7.1 Relative Pressure Sensors

The figure below lists the deviations of the measured values as a function of the cumulative absorbed dose shows us three distinct stages:

A first step between 0 and 23.6 kGy where the measurements remain relatively constant,

A second step where, between 23.26 kGy and 70.75 kGy, the measurement deviations increase sharply and in a linear fashion (from + 1.10% to -9.47%),

A last step from 70.75 kGy where the measurement deviation increases very strongly (vertical drop of the curve).

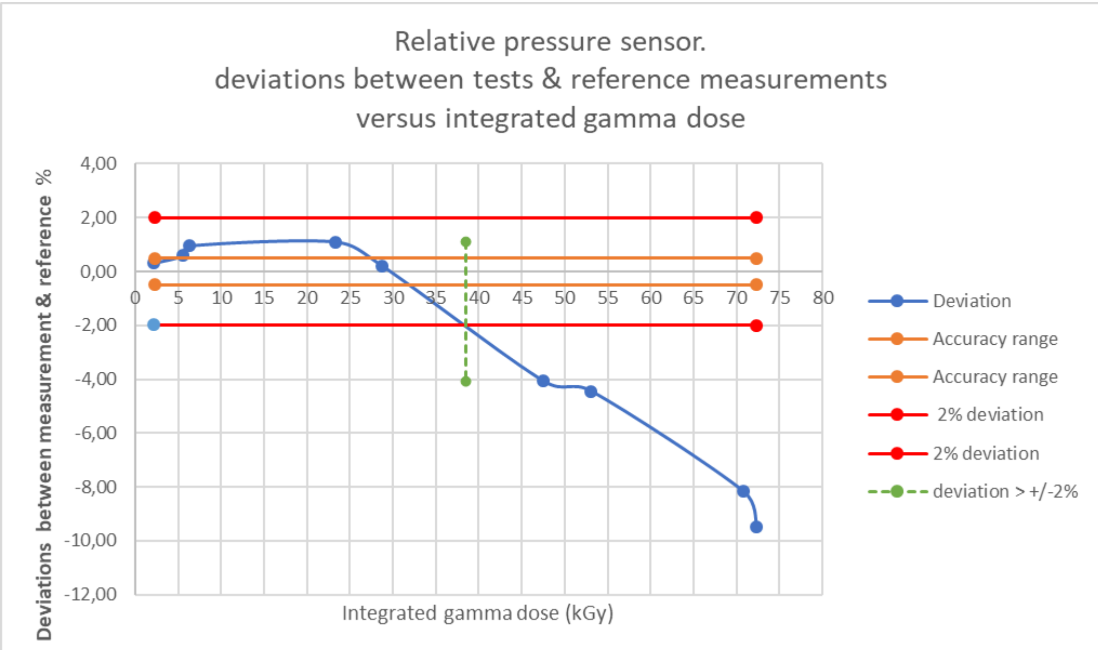


Figure 9: Relative pressure sensor P
Deviations observed between measurements (Y analogic)
& reference sensors (K numeric)
versus integrated gamma dose (kGy)

Note: deviation calculation example.

	FYG relative analogique										
	Input	standard		Measurement							
				down rate		Cumulative dose		deviation			
	bar g	mA	±%	mA	±%	kGy	±%	%			
		Supplier		CVR				(FYG-FYG0)/FYG0*100			
Dose (kGy)		16/06/2021		02/08/2021							
		FYG0		FYG				zero adjustment after irrasiation & before control			
0	0	4,000	0,500	4,002	0,05			0,00	02/08/2021		
2,26	152,5	13,760	0,500	13,802	0,31		-0,500	0,41	03/08/2021		

Comments about the results:

- Note 1: The zero of the sensor was set after each irradiation level before pressurizing the circuit.
- Note 2: some inaccuracies may have slightly modified the first measurements because of the difficulty of maintaining the pressure at a constant value (the pressure falling slowly) or even in adjusting the zero precisely.
  However, we speak of signal deterioration when the ± 2% measurement inaccuracy is exceeded. Such a deterioration is observed between the bearings at 28.78 and 47.56 kGy (-4.08% deviations). Using the curve reading method, it can be determined that the signal emitted by the sensor is deteriorated (exceedance of ± 2%) from 38.4 kGy to higher dose levels.

3.7.2 Differential Pressure Sensors

The figure below lists the deviations of the measured values as a function of the cumulative absorbed dose shows us from the first measurements values outside the precision range and even outside the signal deterioration range. As a result, the measured values have been increased by 2.1% (which corresponds to approximately 0.39 mA) in order to position the first points of the curve within the precision range of the sensor. We then obtain the attached figure.

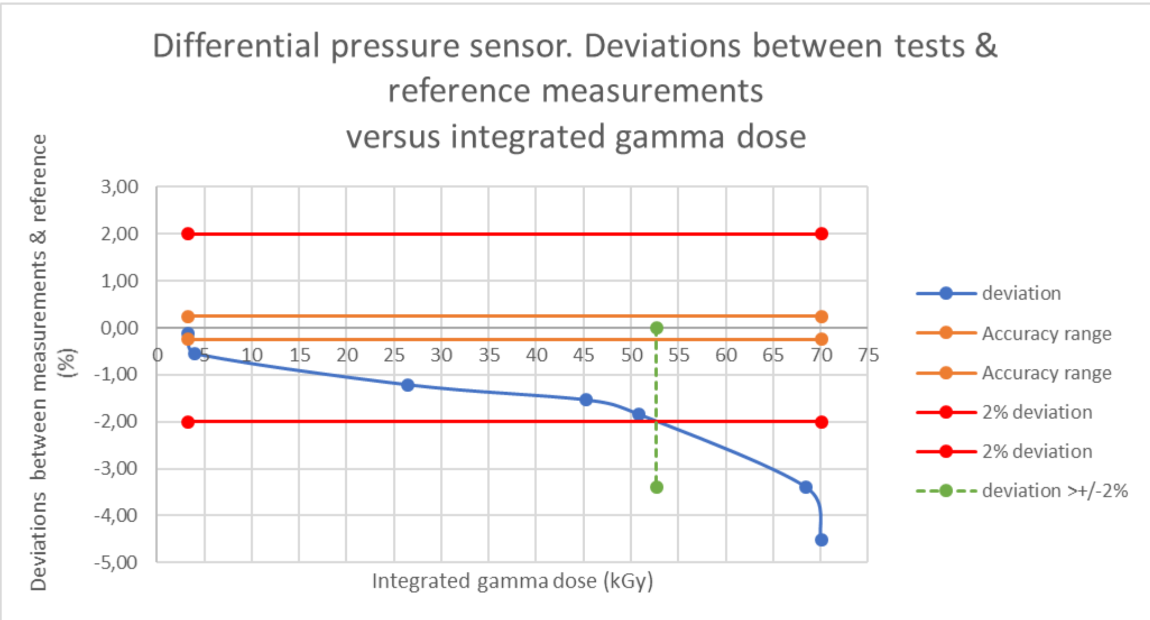


Figure10: Differential pressure sensor P
deviations (after corrections) observed between measurements (Y analogic)
& reference sensors (CVR calibration module)
versus integrated gamma dose (kGy)

The results obtained show us three distinct stages:

- A first stage between 3.31 and 45.3 kGy where the differences increase slightly and in a linear fashion,
- A second stage where, between 45.3 and 68.48 kGy, the measurement deviations increase more strongly, always linearly (from -1.53% to -3.39%),
- A last step from 68.48 kGy where the measurement deviation increases very strongly (vertical fall of the curve).

Note also that the point representing the plateau at 20.99 kGy was not taken into account to plot the curve in fig.10 because that did not correspond to the trend of the curve (hypothesis to be confirmed if necessary by further analyzes of the results).

4. FIRST CONCLUDING REMARKS

The objective for these tests, corresponding to the irradiation of pressure sensors beyond a dose of 70 kGy within 5 days, has been achieved.
The analogue and differential analogue relative pressure measuring sensors received respectively 72.3 kGy and 70 kGy,

Throughout the realisation of the irradiation stages, disturbances linked to the gamma dose absorbed by the sensors could be detected at the level of the output signal.

Indeed, following the plotting of the curves, a correlation between the cumulative absorbed dose and the measurement un-accuracies (deviations between measured value and standard calibration value) could be observed.

Another phenomenon was also highlighted on the two sensors during the irradiation stages: the accentuation of the instability of the output signal (continuous variation of the signal of a few tenths of a mA).

The criterion used to declare the deteriorated signal corresponds to the moment when the measurement deviations exceeded ± 2% / reference signal.

This overshoot has been observed for analogue relative pressure measurement sensors from 38.4 kGy and for analogue differential pressure measurement sensors from 52.7 kGy.

Following this experimental campaign, the results will first be sent to the sensor supplier in order to carry out an expertise.

At the same time, the results will be sent to the JHR ADELINE project team in order to decide on the conformity of these types of sensors with respect to the specifications and thus to validate or not the implementation of this type of sensors on the irradiation loop.

5. REFERENCES

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JHR. The ADELINE irradiation loop in the Jules Horowitz MTR.
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CEA, DEN, CEA CADARACHE, F-13108 Saint-Paul-lez-Durance, France.

[R2] IGORR 2021
JHR Project, France. Irradiation Devices « ADELINE type ».Preliminary Qualification Tests
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