

Assessment of the ^3He pressure inside the CABRI transient rods - Development of a surrogate model based on measurements and complementary CFD calculations

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Abstract—CABRI is an experimental pulse reactor, funded by the French Nuclear Safety and Radioprotection Institute (IRSN) and operated by CEA at the Cadarache research center. It is designed to study fuel behavior under RIA conditions. In order to produce the power transients, reactivity is injected by depressurization of a neutron absorber (^3He) situated in transient rods inside the reactor core. The shapes of power transients depend on the total amount of reactivity injected and on the injection speed. The injected reactivity can be calculated by conversion of the ^3He gas density into units of reactivity. So, it is of utmost importance to properly master gas density evolution in transient rods during a power transient. The ^3He depressurization was studied by CFD calculations and completed with measurements using pressure transducers. The CFD calculations show that the density evolution is slower than the pressure drop. Surrogate models were built based on CFD calculations and validated against preliminary tests in the CABRI transient system. Studies also show that it is harder to predict the depressurization during the power transients because of neutron/ ^3He capture reactions that induce a gas heating. This phenomenon can be studied by a multiphysics approach based on reaction rate calculation thanks to Monte Carlo code and study the resulting heating effect with the validated CFD simulation.

Index Terms—CABRI, ^3He depressurization, CFD, TOP effect.

I. INTRODUCTION

CABRI is an experimental pulse reactor operated by CEA (Commissariat à l'Énergie Atomique et aux Énergies Alternatives) at the Cadarache research center. Since 1978, the experimental programs have been aiming at studying the fuel behavior under Reactivity Initiated Accident (RIA) conditions. In order to study PWR high burn up fuel and new cladding materials behavior under such transients, the facility was modified to accept a pressurized water loop in its central part able to reproduce thermal-hydraulics characteristics representative of PWR nominal operating conditions (155 bar, 300°C). This project, which began in 2003 and supported

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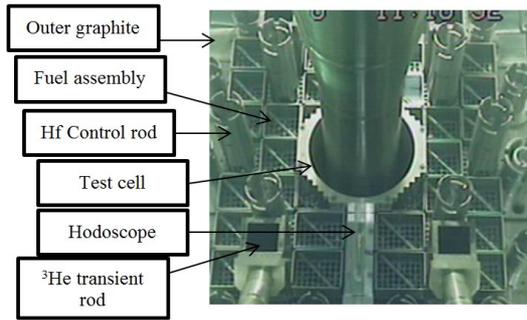
first commissioning power tests from October 2015 to March 2017, was driven within a broader scope including both an overall facility refurbishment and a complete safety review. The global modifications were conducted by CEA. The experiments take place in the framework of the OECD/NEA CIP (CABRI International Program) Project led by IRSN (Institut de Radioprotection et de Sûreté Nucléaire), which financially supports the refurbishment as well as the operational costs of the facility. The CIP program will investigate several fresh and burnt UOx and MOX LWR fuel samples with new cladding materials under RIA conditions, with a foreseen completion by the end of 2023.

Power transients are generated by a dedicated so-called transient rods system [1] allowing the very fast depressurization of ^3He tubes positioned inside the CABRI core. This paper focuses on the study of the ^3He depressurization of CABRI transient rods. The main objective is to properly reproduce the ^3He density evolution in the transient rods situated in the CABRI core, from experimental data provided by pressure transducers situated in the valve and piping system far from the core. The first part of this paper consists of a brief description of the transient rods system. In a second part, the CFD (Computational Fluid Dynamics) approach is addressed. This approach allows the evaluation of state parameters in the entire system and not only at the pressure transducers locations. The last part of the paper deals with the explanation of the TOP effect that affects the depressurization during the transient over power.

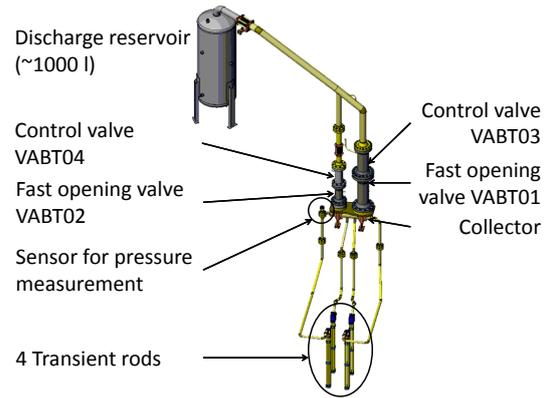
II. CABRI REACTIVITY INJECTION SYSTEM

CABRI is a pool-type reactor, with a core made of 1487 stainless steel clad 6 wo% enriched UO_2 fuel rods. The reactor is able to reach a 25 MW power level in steady state conditions. The reactivity is controlled via a system of 6 bundles made of 23 hafnium control and safety rods. The key feature of the CABRI reactor is its unique reactivity injection system [1]. This device allows the very fast depressurization of the ^3He (strong neutron absorber) into a discharge tank. The ^3He is previously introduced inside 96 tubes (so called "transient rods") located in 4 banks among the CABRI fuel rods (see Fig. 1a).

The CABRI transient rods system is made of the following main components (see Fig. 1b):



(a) Radial view of the CABRI core



(b) Main components of the CABRI transient rods system

Fig. 1. CABRI transient rods system

- 4 fuel assemblies (7x7 pins) equipped on their periphery with 24 tubes instead of 24 fuel rods. The 4 transient assemblies are pressurized to the target pressure (15 bar maximum) by the use of a compressor which pumps the ³He from its storage tank via a devoted circuit.
- From the top of this collector, two flow channels (low and high flow rates) lead to a 1000 l discharge tank set under vacuum before operation. Both channels are equipped with a fast-opening valve (respectively with small and large diameters) followed by a controlled valve.
- A specific control device that triggers the different orders of the experimental sequence as for the opening time of the two fast-opening valves and the shutdown of the reactor control rods.
- Two different pressure transducers measuring the ³He pressure at the inlet of the collector. For design reasons, the ³He pressure cannot be measured directly in the transient rods.

III. CFD SIMULATION OF ³HE DEPRESSURIZATION IN TRANSIENT RODS

The CFD modeling, unlike an analytical approach, can precisely handle complex geometries. The ³He pressure evolution during the depressurization will then be calculated in the entire transient rods system, and not only at the pressure transducers location. The complete validation of the CFD Simulation is described in [2].

The ³He gas depressurization induces a temperature drop in transient rods (see Fig. 2). Assuming an ideal gas, the gas quantity “n” is defined as in (1).

$$n = \frac{PV}{RT} \quad (1)$$

A good state parameter that can be linked to the injection of reactivity is the ³He density, that is proportional to the number of atoms (2).

$$d_{3He} = \frac{nM}{V} = \frac{PM}{RT} \quad (2)$$

The density evolution inside the transient rods is slower than the pressure “P” evolution (see Fig. 3), as temperature “T”

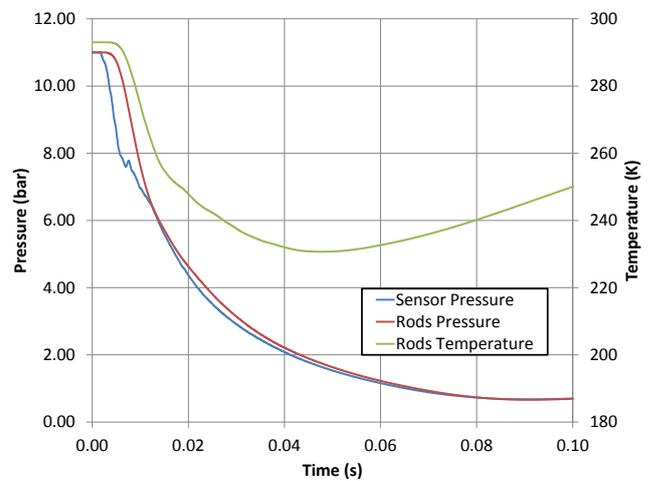


Fig. 2. Helium pressure and temperature evolution during a depressurization according to CFD calculation

varies in about the same proportions. That induces a slower calculated evolution of the reactivity injection.

Several types of surrogate models were built based on validated CFD simulations. The CEA’s URANIE uncertainty platform [3] was used for the surrogate models construction.

In fact, transient rods depressurization is a little different when core power evolves. This little difference can have big effects on power transients. This effect appears when the gas pressure and the core power are both relatively high. It is named “TOP effect” as “Transient Over Power effect”. We can observe it on the pressure curves measured during power transients (Fig. 4).

IV. THE TOP EFFECT

The TOP effect comes from ³He heating during power transients. As power increases, the thermal neutron flux also increases. So, the neutron absorption by ³He intensifies. This reaction produces two charged particles : proton and tritium. One part of their energies is deposited in the ³He gas by ionization before reaching the metallic wall of the transient

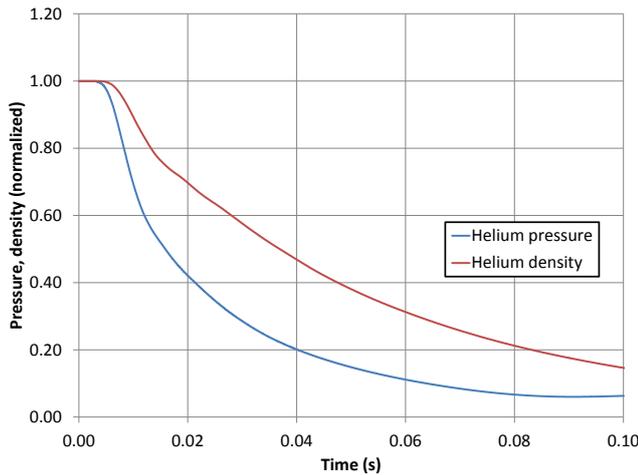


Fig. 3. Helium pressure and density evolution during a depressurization according to CFD calculation

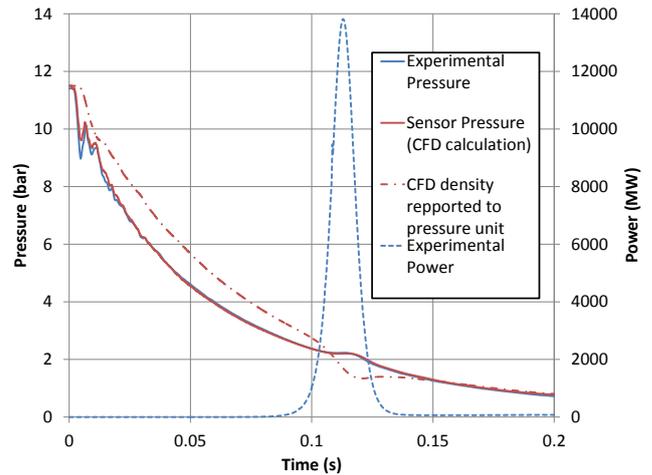


Fig. 5. CFD calculation of simple depressurization by high flow rate channel (VABT03 aperture $\sim 40\%$) including TOP effect

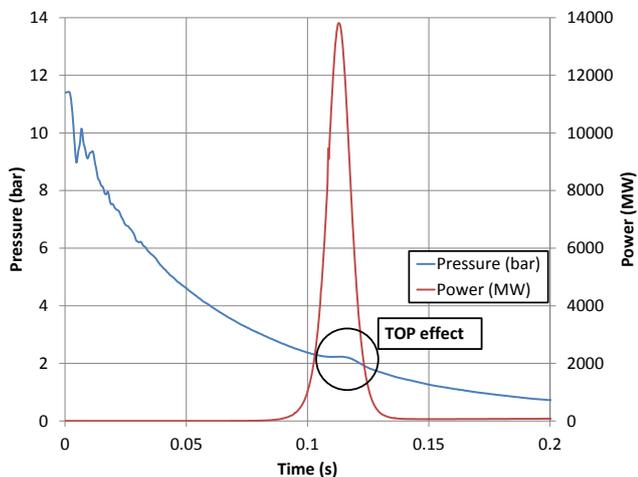


Fig. 4. TOP effect visualization on a recent CABRI power transient (2017)

rods. Denser is the gas, higher the probability of ionization is and more important the deposited energy is. The direct effect of this energy deposit is that the gas temperature increases. A temperature increase is equivalent to a pressure increase. The pressure gap between rods and flow channels implies a faster depressurization of helium from the transient rods. This finally implies a rise of the reactivity injection speed. The TOP effect increases the maximum power and the energy deposit. For relatively slow transients (at least 20 ms FWHM), it can represent more than the half of the maximum power and at least 30 % of the energy deposit. Thus the TOP effect has to be taken into account in order to have an accurate predictive tool.

We simulated a depressurization by entering the experimental power and a function linking power, helium density and helium function, in the existing simulation. Results of this simulation are plotted on Fig. 5. We can observe that density is decreasing faster at the moment of the peak, resulting in an increase of the injected reactivity.

V. CONCLUSIONS

The present study points out differences between measured pressure and ^3He density in transient rods. It shows that the gas density evolution is slower than pressure evolution because of temperature changes in the rods. Surrogate models were developed in order to replace old models based on analytical solution of the problem (with simplification of the geometry). The study demonstrates that the ^3He density evolution is different if core power is boosted due to gas heating by neutron/ ^3He interactions. This effect, named TOP effect, affects density evolution by increasing depressurization speed during the transients. It explains some difficulties in the CABRI power transients prediction. Surrogate models are in development in order to be used in future power transients calculations.

APPENDIX A NOMENCLATURE

Name	Definition
n	Amount of substance of the gas (in moles)
P	Pressure
V	Volume
R	Gas constant ($8.314 \text{ J.K}^{-1}.\text{mol}^{-1}$)
T	Absolute temperature
$d_{^3\text{He}}$	Mass density of the gas
M	Molar mass of the gas

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