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M Gerard, Y Pontillon, J Sercombe, V d'Ambrosi, T Doualle, et al.. Development and Modeling of Laser Experiments for Central Hole Formation in PWR Fuel Pellets. ICAPP 2025 – International Congress on Advances in Nuclear Power Plants, Sep 2025, Juan-Les-Pins, France. <hal-05520976>

HAL Id: hal-05520976

<https://cnrs.hal.science/hal-05520976v1>

Submitted on 20 Feb 2026

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Development and Modeling of Laser Experiments for Central Hole Formation in PWR Fuel Pellets

M. GERARD^{1,2 (a)}, Y. PONTILLON¹, J. SERCOMBE¹, V. D'AMBROSI¹, T. DOUALLE¹
and L. GALLAIS²

¹CEA.DES.IRESNE.DEC, Cadarache, F-13108 Saint-Paul-Lez-Durance, France

²Aix Marseille Univ, CNRS, Centrale Med, Institut Fresnel, Marseille, France

^(a) Corresponding Author, E-mail: maxime.gerard@cea.fr

KEYWORDS: *Laser heating, Central hole, Porosity migration, PWR Fuel, Simulations*

Introduction

One of the fundamental requirements for the safe operation of Pressurized Water Reactors (PWR) is to limit fuel melting. In France, centerline fuel melting volume fraction must be lower than 10 % of pellet volume as fuel safety criteria require. Today, there are still open questions regarding the mechanisms involved and their impact on fuel performance [1]. In this context, the experimental irradiation project Power to Melt and Maneuverability (P2M), initiated in 2021 as part of the OECD/NEA FIDES-II initiative [2], aims at providing new data on fuel behavior during slow transients, conducted at very high power levels, leading to incipient centerline fuel melting without cladding failure. Very few data are today available for this type of scenario. Most data come from the xM3 Irradiation. At the Studsvik R2 reactor in 2005, the xM3 fuel rod segment, previously irradiated at 30 GW/dtU in a PWR, underwent a stepwise power ramp up to extremely high Linear Heat Rates (LHR) and temperatures [1] [3]. As illustrated by the ceramography of Figure 1, the experiment led to the formation of a central hole at the pellet center that was attributed to fuel melting.

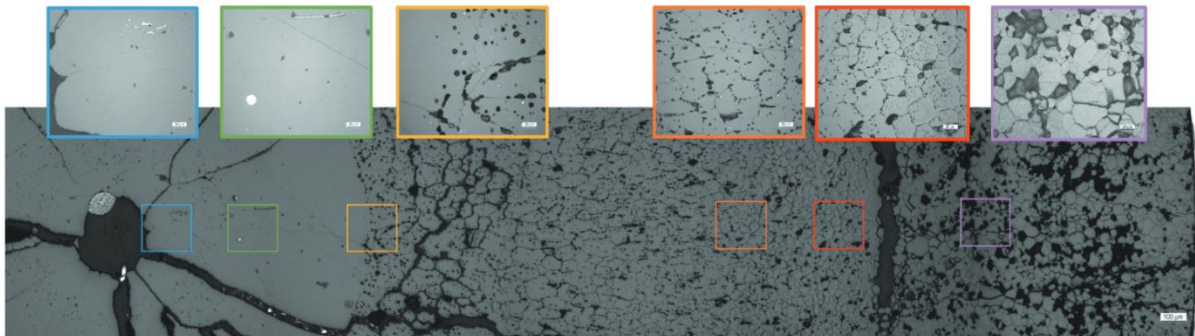


Figure 1 : Overview and details of the etched fuel cross section cut near the Peak Power Node after the xM3 power ramp

However, fuel performance simulations indicate that during slow power ramps, a central hole may form in the fuel ceramics due to restructuring driven by pore migration along the radial temperature gradient [1]. Under reactor conditions, this gradient develops between the hot pellet center and the cooler periphery, influencing the pores within the fuel pellet. The temperature difference in the pores leads to fuel vaporization in the hottest region and condensation in the cooler part, causing pore migration toward the pellet center [4]. The formation of a central hole affects the thermal and mechanical properties of the fuel. Thermal conductivity increases near the central hole due to the reduced porosity, leading to a decrease in pellet temperature and radial deformation, thereby shifting fuel melting to higher power levels. Therefore, it is essential to determine whether the central hole in nuclear fuel pellet forms before, during or after initiation of fuel melting.

The objective of this work is to investigate the behavior of PWR fuel pellets under extreme conditions and, more precisely, to study by laboratory experiments the potential formation of a central hole due to

pore migration up the thermal gradient. First, this paper details the 1D model used to confirm the feasibility of central hole formation in short time, compatible with laboratory experiments. Second, the laser heating experiment developed to replicate these extreme conditions while preserving the structural integrity of the fuel is described. Then, 2D thermo-mechanical simulations of this experiment are proposed and validated by experimental data of temperature profile measurements. Finally, a general conclusion with perspectives for future improvements of the models are provided.

1. The 1D model for analyzing the feasibility of central hole formation

This section details the development of 1D model designed to assess whether a central hole can form within a reduced timescale using a simplified power ramp, as shown in Figure 2. This model is crucial as it determines part of the experimental conditions required to reproduce the phenomenon while ensuring feasibility within laboratory constraints. It plays a central role in understanding the thermal conditions governing pore migration and central hole formation, specifically evaluating whether a simplified power ramp can achieve the expected results within a few hours.

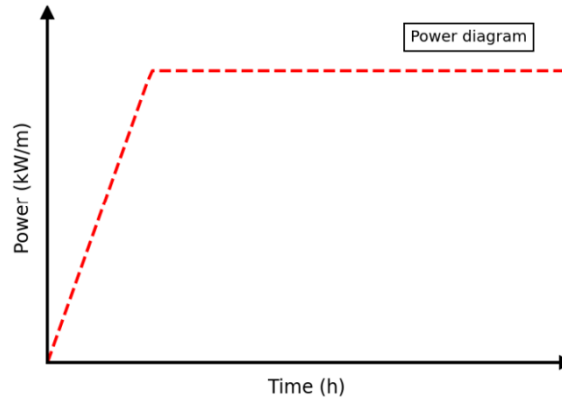


Figure 2 : Simplified power loading, modified to meet feasibility constraints for central hole formation within a short timescale.

The feasibility of this approach is tested by implementing a 1D model where the heat equation (1) and the pore advection equation (2) are coupled to simulate the migration mechanism in a fuel pellet system formulated in cylindrical coordinate system [5].

$$\rho C_p \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(r \lambda(T, p) \frac{\partial T}{\partial r} \right) + \frac{1-p}{1-p_0} \frac{f(r) P_1}{4\pi R^2} \quad (1)$$

$$\frac{\partial p}{\partial t} = -\frac{1}{r} \frac{\partial}{\partial r} (r v p) \quad (2)$$

Where p is the porosity at time t , v the pore velocity in [m/s], P_1 the Linear Heat Rate in [W/m], R the outer radius of pellet in [m], ρ the fuel density in [kg/m³], C_p the heat capacity in [J/K/mol], λ the thermal conductivity in [W/m/K] and p_0 the initial porosity.

In equation (1), the thermal conductivity evolves with porosity. Additionally, the pre-factor of the power term $\frac{1-p}{1-p_0}$ ensures that when the porosity reaches 1 (i.e., when a central hole is formed), the power is locally zero.

To solve equation (2) we use the expression of the pore migration velocity proposed by P. F. Sens [6], which depends on the temperature, the thermal gradient, the heat of vaporisation of the oxide and the local vapor pressure :

$$v = C_0 (C_1 + C_2 T + C_3 T^2 + C_4 T^3) \Delta H \frac{P_0}{T^{2.5}} \exp\left(-\frac{\Delta H}{RT}\right) \frac{\partial T}{\partial r} \quad (3)$$

Where $\frac{\partial T}{\partial r}$ is the radial temperature gradient in [K/m], ΔH the heat of vaporization and $P_0 \exp\left(-\frac{\Delta H}{RT}\right)$ the

vapour pressure of UO_2 in equilibrium with the solid at the pore surface.

This model has previously been used to analyse xM3 power ramp, showing that a central hole due to pore migration could have formed during the experiment. It also explains the formation of a densified fuel ring next to the hole [1]. Simulations indicate that the LHR below 55 kW/m have no influence on porosity migration during the xM3 power ramp, as the local temperature remains too low.

To study pore migration with the 1D model, simulations of a fuel pellet and cladding submitted to a straight power ramp (cf. Figure 2) are performed: the power is linearly increased up to a LHR between 55 and 70 kW/m that is maintained during a few hours. The pore migration model allows to estimate if a central hole forms. The simulations are performed assuming an initial porosity of 5% and a pellet radius of 4.1 mm. The thermal properties (heat capacity, thermal conductivity) are those used in the fuel performance code ALCYONE of the PLEIADES platform [7].

Figure 3 shows the evolution of the calculated quantities of interest for the design of the laser experiment during the power ramps. Figure 3 (a) presents the calculated radial temperature profiles after 6 hours of holding period at maximum power. These radial temperature profiles are the references used to pre-design the laser experiment. Figure 3 (b) shows the calculated kinetics of the central hole radius during the power ramp. Figure 3 (c) gives the calculated radial profiles of porosity. These two last graphs are used to estimate whether the formed central hole is sufficiently large to be observed after a few hours thermal loading.

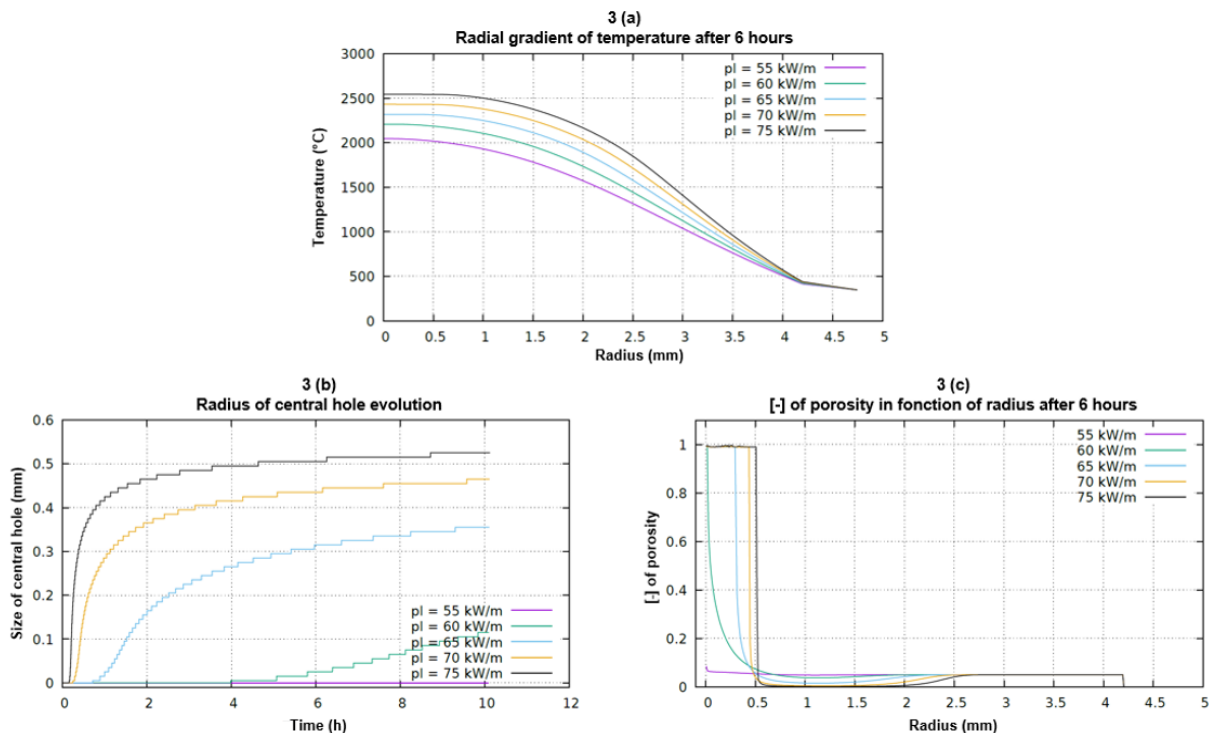


Figure 3 : Simulation results of the power ramps at different maximum LHR (55 to 75 kW/m). 3(a) Radial gradient of temperature after 6 hours of different maximum LHR. 3(b) Calculated evolutions of central hole radius over time for different LHR. 3(c) Radial distribution of porosity after 6 hours of maintaining the power plateau.

This simulation performed at a LHR of 70 kW/m (yellow curves), shows that the temperature at the center of the pellet (2450°C) remains well below the fuel melting temperature (2800°C) [8]. Additionally, the radial temperature profile obtained during the power plateau leads to the formation of a central hole with a radius of 0.45 mm in 6 hours, which is considered sufficient for visual observation.

2. Development of the laser experiment for central hole formation

In this section, an experimental setup designed to reproduce the formation of central hole by controlled laser heating of a UO_2 disc is presented. The laser experiment takes place at the Fresnel Institute in Marseille, which allows only non-irradiated UO_2 fresh samples. Figure 4 presents a conceptual diagram of the experimental setup developed for central hole formation. In the following sections, the description of the various components of the setup will be provided and will refer to specific parts of this diagram.

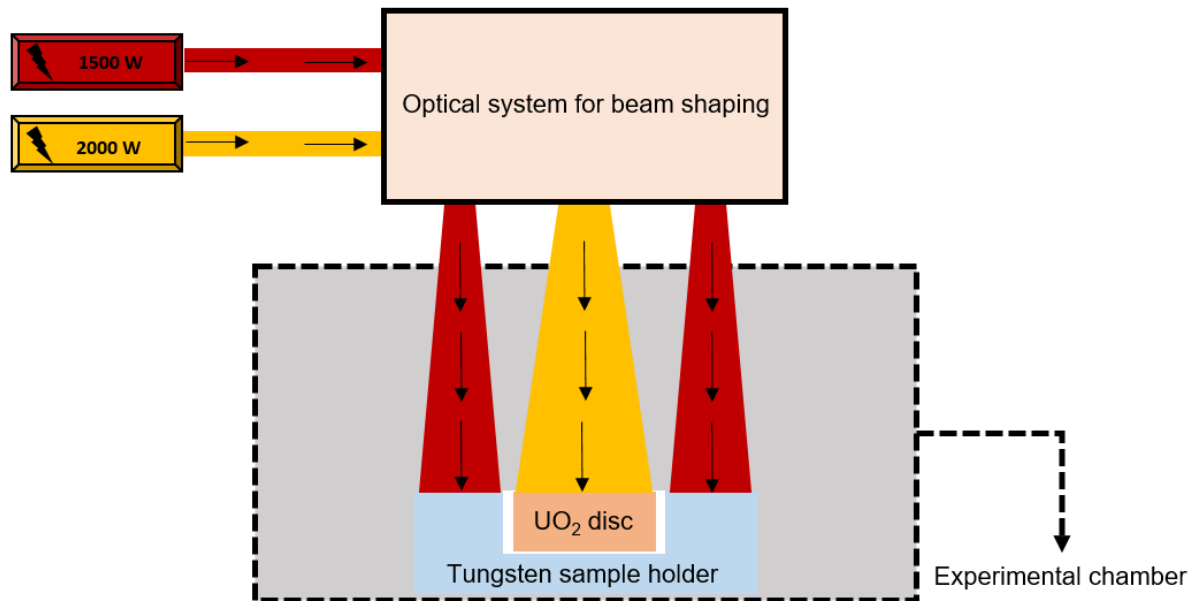


Figure 4 : Conceptual diagram illustrating the overall configuration of the experimental setup designed for central hole formation in a 1 mm thick fresh UO_2 disc.

2.1. The VULCAN experimental chamber

The development of a laser experiment dedicated to central hole formation involves several experimental constraints.

First, as estimated in section 1, the activation temperatures for the porosity migration occur at very high temperatures and require the UO_2 disc to be placed on a support capable of withstanding these extreme conditions. To achieve this, a tungsten sample holder, specifically designed to contain an 8.2 mm diameter UO_2 disc has been manufactured (cf. Figure 5). With its high melting point (3422 °C) and very low thermal expansion (4.5 $\mu\text{m}/(\text{m.K})$), tungsten is an ideal material for the sample holder.

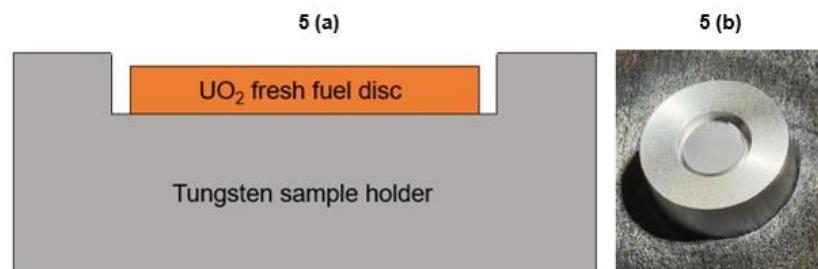


Figure 5: 5(a) Scheme representation of the cross-section of the sample holder system and of the sample. 5(b) A picture of the sample holder containing a UO_2 disc.

Second, considering the material used and the thermal conditions required for central hole formation, the UO_2 disc must be placed in an experimental chamber to minimize risk during the laser experiment.

Additionally, to prevent sublimation and oxidation of the sample holder and UO_2 disc, the chamber must be perfectly sealed and filled with an inert gas, such as argon, at a pressure of 1.5 bar.

To meet these requirements, an experimental chamber called VULCAN (Versatile Unit for Laser-Controlled Atmospheric Nuclear studies) is designed. It is represented with a dashed box in Figure 4. The experimental chamber (cf. Figure 6) containing the sample holder system and the sample is fully sealed and can reach a primary vacuum of 1.1×10^{-3} mbar. It can operate under argon atmosphere at a pressure of 1.5 bar, is actively cooled and includes several viewing ports for real-time observation, measurement and laser beam paths.

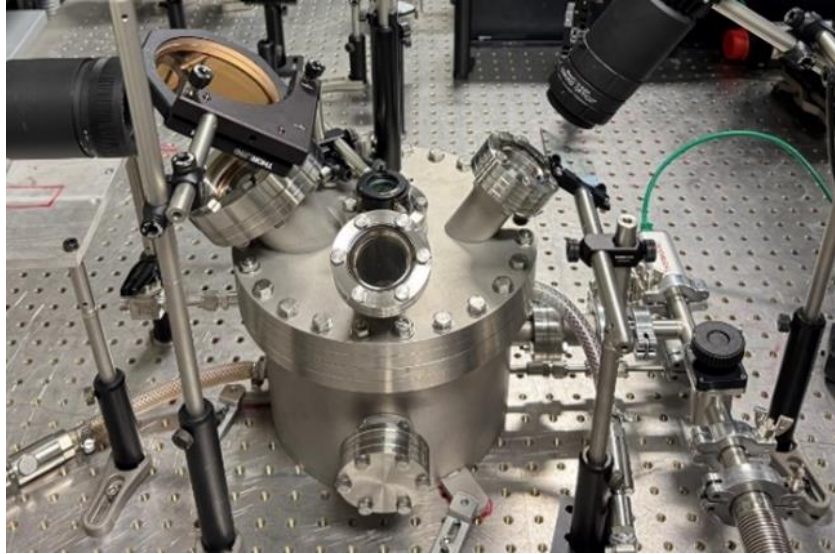


Figure 6 : The VULCAN experimental chamber installed on the optical table

2.2. Preheating and Heating high power laser systems

To achieve the radial temperature profile described in section 1, a laser-controlled heating system is employed. However, generating a radial temperature gradient inevitably induces mechanical tensile and compressive stresses, which may cause cracking or even fracture the fuel disc within the sample holder. To mitigate this, a dual high power laser system (kW-class Ytterbium lasers operating at $1 \mu\text{m}$ wavelength) has been implemented.

In order to avoid tensile and compressive stresses induced by radial temperature gradient on the UO_2 disc during the experiment, a preheating laser, shown in red in Figure 4, is employed. This laser, capable of delivering 1500 W of power, emits a laser beam that, after passing through a series of optics, produces an annular beam with a 20 mm diameter and 5 mm thickness. This beam is directed onto the front face of the tungsten sample holder, without affecting directly the UO_2 disc placed inside. The main objective of the preheating laser is to heat the rear face of the UO_2 disc by conduction and to raise the temperature of the disc surfaces by heat radiation. As a result, the disc temperature increases uniformly until thermal creep is activated, allowing the relaxation of stresses and therefore maintaining the mechanical integrity of the disc.

Once this preheating phase is completed, the heating laser, depicted in yellow in Figure 4, capable of delivering 2000 W, directs a super-Gaussian beam through an optical system that adjusts the size of the

beam and focuses it exclusively onto the front face of the UO_2 disc. This beam creates a radial temperature gradient, enabling the fuel disc to reach the activation temperature required for the porosity migration phenomenon (2450°C), as illustrated in Figure 7.

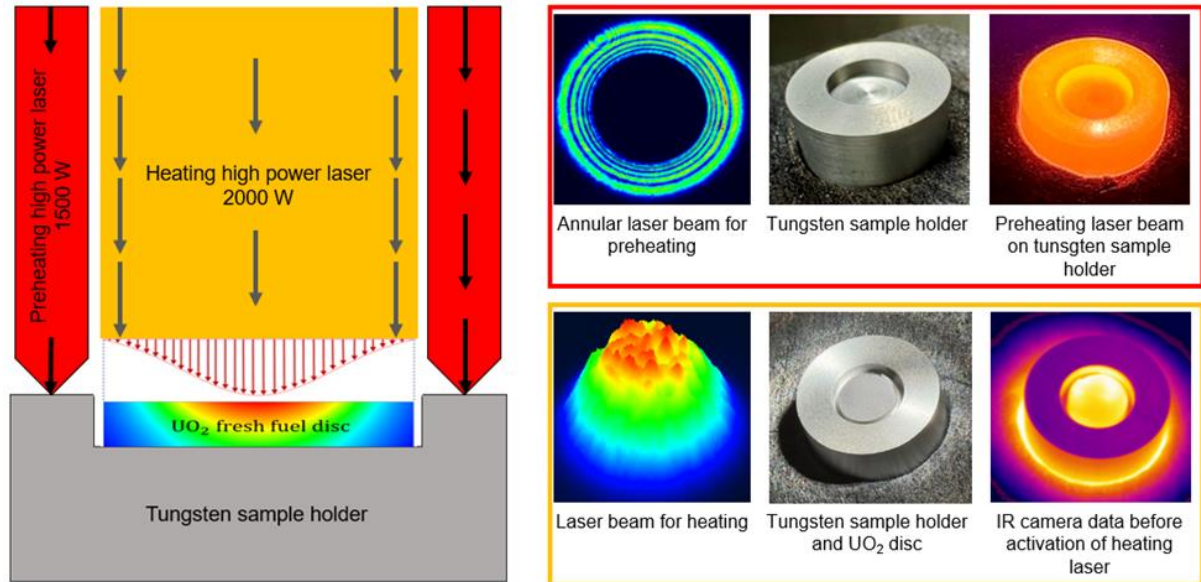


Figure 7 : Left: schematic representation of the preheating and heating lasers applied respectively to the tungsten sample holder and UO_2 disc. Top right red box: 2D radial cartography of preheating laser on the sample holder, picture of the sample holder and of the sample holder during the preheating phase. Bottom right yellow box: the 3D cartography induced by the heating laser is shown, picture of the sample holder containing the UO_2 disc, and picture from the infrared camera taken at the end of the preheating phase, confirming that preheating preserves the structural integrity of the disc.

2.3. Experimental instrumentation for central hole formation

The instrumentation of the central hole formation experiment presents several challenges. Since the UO_2 disc is placed inside the experimental chamber, direct visibility is significantly reduced. Moreover, the extreme temperatures required for central hole formation generate intense thermal radiation, making observation with a standard visible camera impossible. To address these constraints, a dedicated set of instrumentation has been designed for real-time monitoring and measurement.

Pressure and temperature control in the VULCAN experimental chamber relies on multiple systems. A vacuum gauge with a display allows real-time monitoring of the chamber's pressure before filling it with argon. Once the primary vacuum is reached, flow and pressure regulators are installed at the chamber's inlet and outlet, with a real-time display of the internal gas pressure. Thermocouples are placed at the cooling circuit inlet and outlet to control that the chamber remains at room temperature.

For real-time visual observation, a logarithmic response camera has been installed to compensate for the high contrast between the UO_2 disc, the tungsten sample holder, and the chamber background. This camera ensures a clear, saturation-free visualization of the central hole formation process.

Finally, for thermal measurements, an infrared camera is used to assess the temperature distribution at the periphery and center of the fuel disc. Two pyrometers are positioned around the chamber to measure the front and side temperature of the tungsten sample holder.

This comprehensive instrumentation ensures precise real-time monitoring of thermal and atmospheric conditions while providing accurate and reliable observations of the central hole formation process. However, the analysis of experimental data and simulation based on the 1D model do not fully capture

the experimental conditions or allow for an optimal processing of results. Therefore, alongside the experimental development, a 2D model has been designed to more accurately simulate the experimental conditions. This model is presented in the following section.

3. The 2D model for thermomechanical radiation-matter interaction

As explained in the previous section, the 1D model simulate a fresh fuel pellet and allows for the estimation of the temperature gradient required for the activation of pore migration but does not accurately replicate the laser heating experiment developed for this purpose. To address this limitation, a 2D thermomechanical model has been developed to analyze laser-matter interactions in this experiment. It includes the heating laser on the fuel disc and the impact of the preheating laser on the tungsten sample holder.

This model considers a UO_2 fuel disc with a manufacturing porosity of 5%. The disc has a thickness of 1 mm and a diameter of 8.2 mm. It rests in a 10.2 mm diameter cavity inside the tungsten sample holder which measures 20.2 mm in diameter and 10.2 mm in thickness. Due to the axial symmetry, only half of the system (disc and sample holder) is simulated. Figure 8 illustrates the system's mesh, with a density of $2.5 \mu\text{m}$.

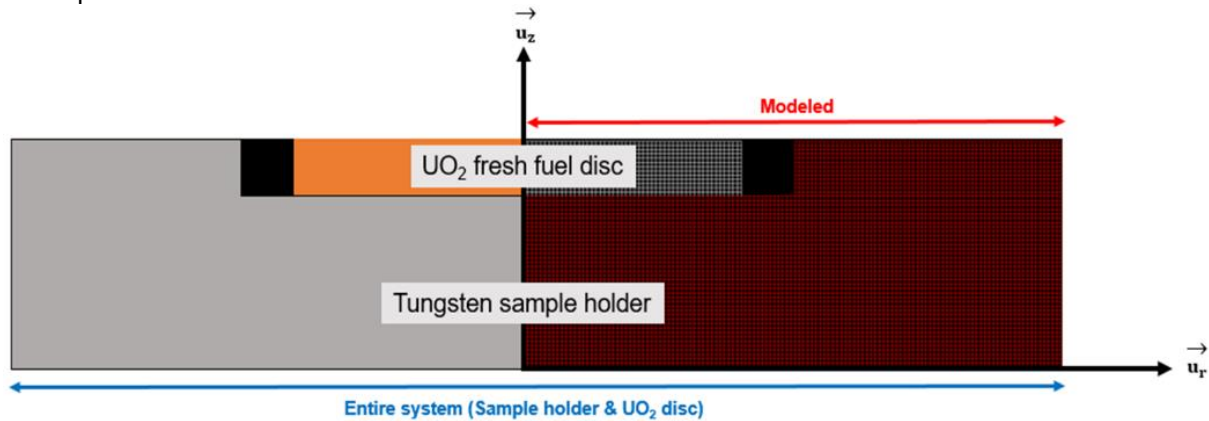


Figure 8 : Finite element mesh used in 2D(r,z) simulation

3.1. Preheating and heating laser loading implementation in 2D model

In the 2D model, the laser loading for both the preheating and heating beams can be defined using intensity functions either with radial dependence, representing a surface or volume power deposition, or by directly implementing the actual laser profiles obtained experimentally. In this study, the preheating and heating laser loading are respectively modeled by using an annular Gaussian profile and revolution

Gaussian function, as illustrated in Figure 9.

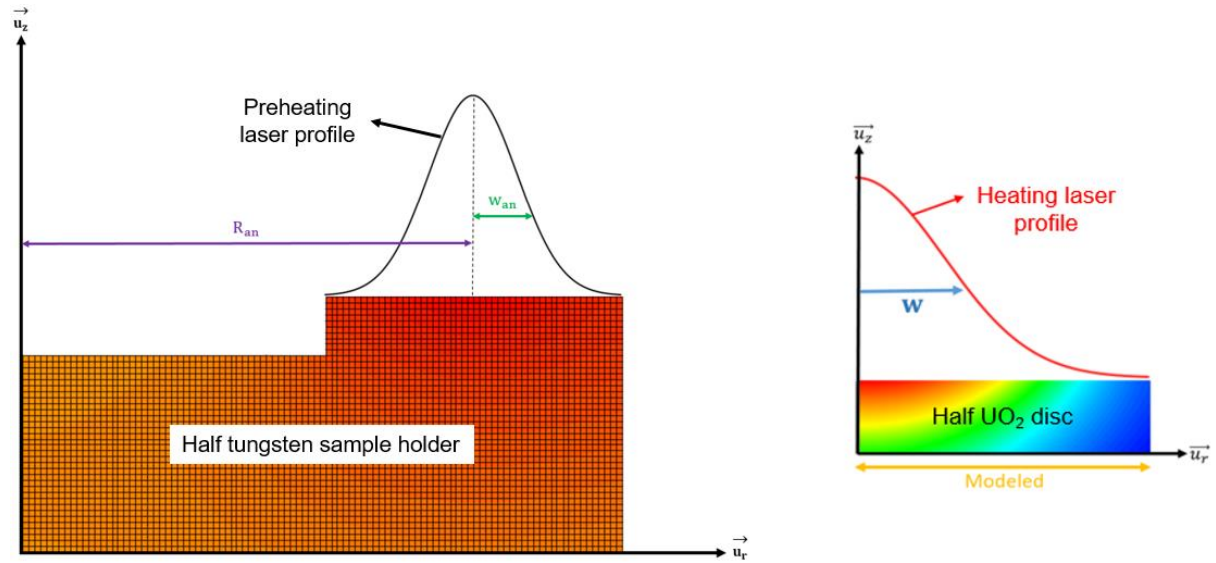


Figure 9 : Annular Gaussian preheating laser loading applied on tungsten sample holder and Gaussian heating laser beam applied on the fuel disc with for both an example of thermal field generated respectively in the sample holder and disc.

The preheating laser is represented by a Gaussian annular beam, as described by M. Reymond et al. [9]. This beam is characterized by its annular radius R_{an} , centered on the upper edge of the tungsten sample holder, and its waist w_{an} , set at 2.5 mm corresponding to half the thickness of the beam. The beam is applied perpendicularly to the upper surface of the sample holder (cf. Figure 7), considering an absorption coefficient of 33% for the power laser wavelength emitting in near infrared, based on the work of M. Minissale et al. [10].

The heating laser is implemented as a volumetric power deposition with a Gaussian shape, as shown in Figure 9 and Figure 7. The intensity of the laser beam in $[W/m^3]$ is defined as follows [11]:

$$I(r, z) = \frac{2P}{\pi w^2} \cdot \exp\left(-2\frac{r^2}{w^2}\right) \alpha \cdot \exp(-\alpha z) \cdot (1 - R) \cdot f(t) \quad (4)$$

With P the laser power in $[W]$, r , the radial position within the pellet in $[m]$, z , the axial position from the upper surface of the pellet in $[m]$, w , the waist of the laser beam in $[m]$, which is the radius at which the intensity is reduced by a factor of $\frac{1}{e^2}$ compared to its maximum value at the center, $(1 - R)$ with R the ratio of reflected flux to incident flux [12], $\alpha = \frac{1}{\delta}$ is the material absorption coefficient in $[1/m]$ which is the inverse of the laser penetration depth in $[m]$ into the material and $f(t)$ is a normalized function describing the temporal evolution of the intensity.

3.2. Thermomechanical boundary conditions in the 2D model

The radiative flux in this model is defined over the entire periphery of the system. Thermal radiative boundary conditions are imposed on the front face and the wall of the UO_2 disc, as well as on the gap between the disc and the inner surface of the tungsten sample holder, including its entire periphery and expressed in $[W/m^2]$ as follows:

$$\phi = \sigma \varepsilon (T_e^4 - T^4) \quad (5)$$

With ε respectively the emissivity for UO_2 and for the tungsten sample holder, σ the Stefan-Boltzmann constant ($5,669 \cdot 10^{-8} [W/m^2/K^4]$), T_e the temperature of the external environment in $[K]$ and T the surface temperature of the materials in $[K]$.

The lower face of the UO₂ disc is assumed to be in perfect contact with the tungsten sample holder. The emissivity of UO₂ is taken from the report of IAEA [13], while those of tungsten are based on the study of M. Minissale [10].

The mechanical behaviour is solved only for the fuel disc using a viscoplastic model [14] [15]. This model incorporates tabulated values of Young’s modulus and Poisson’s ratio, which are defined as a function of temperature and porosity, along with a thermal expansion coefficient dependent solely on temperature. The objective is to model the stresses induced by the laser preheating and ensure that the disc does not crack or fracture. The activation of creep at the pre-heating temperature ensures a partial relaxation of stresses that is expected to limit fuel cracking when the laser heating is applied.

3.3. Experimental validation of the 2D model during the preheating phase

To validate the 2D thermomechanical model, a preheating test is conducted. The instrumentation detailed in section 2.3 is used to measure the temperature of the tungsten sample holder as well as the peripheral and central temperatures of the UO₂ disc.

The test consists of a complete preheating ramp. It starts with a stabilization plateau at 10% of the laser maximum power (150 W) for 10 minutes, followed by a linear increase in 10 minutes to reach 50% power (750 W). This plateau is maintained for 15 minutes to ensure that the UO₂ disc does not crack or fracture. The power is then gradually reduced in 5 minutes back to 10%, followed by a final 5 minutes plateau before turning off the pre-heating laser.

The preheating laser power ramp is incorporated into the 2D model to perform thermal simulations on the tungsten sample holder and thermomechanical simulations on the fuel disc.

Figure 10 compares the experimentally measured temperatures of the sample holder and UO₂ disc (solid curves) with the temperatures simulated by the 2D model. To the right of the graph, three outputs from the 2D model illustrate (from the top to the bottom) a 2D temperature map of the fuel disc, of the circumferential stresses, and of the creep equivalent strain. These data are extracted at the 50% power plateau, where the temperature is the highest.

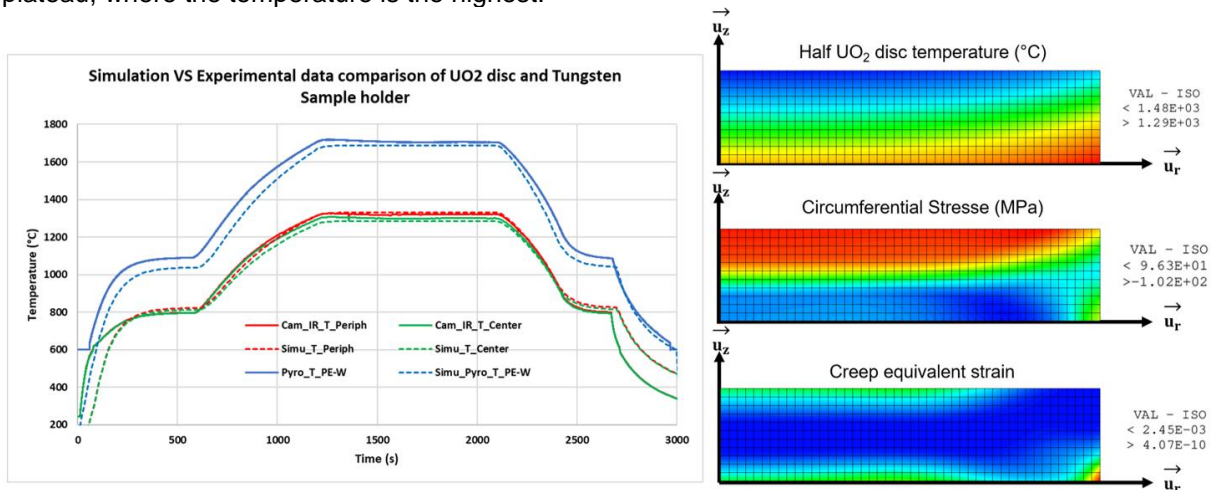


Figure 10 : Comparison between the temperature measurements on the sample holder and UO₂ disc and calculated temperatures from 2D model

The analysis confirms the accuracy and reliability of the 2D model. Although minor temperature differences (less than 5%) appear at certain points between the experimental data and the simulated temperatures of the sample holder, these differences remain negligible. Additionally, the mechanical results indicate that the tensile and compressive stress levels in the fuel disc do not reach the UO₂ fracture threshold (150 MPa). Furthermore, the disc begins to relax its internal stresses before reaching the 50% power plateau (non negligible creep strains), aligning with experimental observation: after preheating, it remained intact.

Conclusion

This study presented the results of a 1D model aiming at reproducing the thermal evolution and pore migration in a fuel pellet submitted to a power transient. This model, developed as a preliminary step, validated the feasibility of a central hole formation within a few hours, therefore showing the potential reproduction of this phenomenon at laboratory scale by a laser heating experiment.

To experimentally reproduce the formation of a central hole by laser heating, a dedicated experimental setup was manufactured, incorporating a specialized chamber and an advanced instrumentation system. In parallel, a 2D model was created to accurately simulate the laser heating experiment, accounting for irradiation-matter interactions and resulting thermomechanical effects. This model enabled the assessment of radial and axial temperature distributions as well as the tensile and compressive stresses distributions in the fuel disc, providing valuable insights into the UO₂ pellet behavior at high temperatures.

In the next steps, the heating laser will be combined with a preheating laser to ensure the final temperature increase required to the formation of a central hole. The 2D model will be used to determine the optimal laser power, shape and dimensions necessary to achieve the desired radial temperature gradient. A coupling with the 1D model will then allow for the estimation of the time required and size of the central hole formed by the heating laser. Furthermore, integrating the 1D pore migration model into the 2D thermomechanical framework is planned to further refine the simulations.

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