# Ignition and spread of a *"smouldering"* front in porous media

**— Application to zombie fires issue —**

## 1. Background

The risk of wildfires is particularly high in the Nouvelle-Aquitaine region of France. In recent years, several large-scale fires, such as the Landiras fires of 2022, have underscored the severity of this issue. Due to the geological specifics of certain areas in the Nouvelle-Aquitaine region, characterized by the presence of peat and lignite, a new type of fire propagation has been observed : ***"the zombie fires"*** – Fig.2.

FIGURE 1 – *Smouldering process*

These underground fires pose a major challenge due to their difficulty in detection and control. They can reignite surface fires initially considered extinguished, as was the case in Landiras in 2022, where a resurgence led to the destruction of an additional 7,400 hectares.

To address these challenges, the Nouvelle-Aquitaine region funds the PSGAR (Large-Scale Scientific Project) GRIFON project (Management of Multiple Forest Risks in Nouvelle-Aquitaine), which includes this work on zombie fires.

## 2. Research focus and methodology

The research project focuses on the experimental and numerical study of *"underground"* fires, also known as *"zombie"* fires. This type of fire typically develops in peat-rich soils with combustible organic matter, such as lignite.

The underground combustion is governed by several coupled phenomena :

- **Heat and mass transport** in porous media
- **Pyrolysis reactions** of organic matter
- **Oxidation reactions** (smouldering) involving oxygen diffusion within the porous medium (soil)

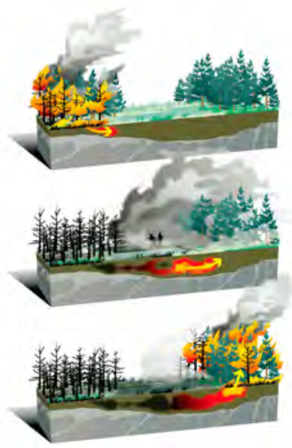

FIGURE 2 – *Zombie fire*

This type of reaction, termed ***"smouldering"*** – Fig.1 – is characterized by slow propagation kinetics, facilitated by the highly exothermic nature of the process. These fires can persist for extended periods, even under unfavorable conditions (moisture, absence of external heat flux) and, in certain circumstances, reignite surface fires.

The adopted methodology is based on a detailed study of three key processes :

1. **Ignition** of the smouldering process
2. **Propagation** of the reaction front (smouldering + pyrolysis)
3. **Surface ignition** and transition to a crown fire

These three aspects will be studied using a combined approach :

- An **experimental** study at the laboratory scale, aimed at reproducing and analyzing the development conditions of zombie fires in a controlled environment
- A **numerical** study aimed at modeling underground fire propagation using advanced simulation tools

## 2.1 Experimental study

Figure 3 – *Cone calorimeter*

The study involves the design and instrumentation of an experimental setup (*"zombie bench"*) to reproduce conditions conducive to the smouldering process in peat soils.

The setup will include instrumentation combining several measurement methods :

— **High-speed and thermal (IR) cameras** : to analyze the spatiotemporal dynamics of ignition and propagation of the smouldering front

— **Radiative and convective flux meters** : to characterize the thermal balance at the surface of the porous medium

— **Thermocouples** : to measure the thermal gradient within the sample and identify critical ignition temperatures

— **Gas analyzers (Fourier Transform Infrared – FTIR)** : to monitor pyrolysis and oxidation reactions in real-time

The experiments will aim to :

1. Study the influence of environmental conditions (temperature, humidity, heat flux) on the ignition of the smouldering front
2. Characterize propagation mechanisms based on the properties of the porous medium (porosity, composition,...)
3. Analyze conditions favoring the ignition of surface vegetation cover

## 2.2 Numerical study

The numerical approach involves the development and validation of an underground fire propagation model.

This model will be implemented within the **PATO (Porous Analysis Toolbox based on OpenFOAM)** simulation code, originally developed by **NASA** for thermal shield calculations of spacecraft.

Specific models have been implemented in the PATO code to address biomass combustion and fire propagation issues.

The modeling will follow a multi-scale approach to account for the various physicochemical phenomena involved :

— **Microscopic scale** ($\sim$ 1 mm) : characterization of reaction kinetics by thermogravimetric analysis (TGA)

— **Mesoscopic scale** ($\sim$ 10 cm) : characterization of heat and mass transfers using a cone calorimeter – Fig.3.

— **Macroscopic scale** ($\sim$ 1 m) : complete modeling of the propagation process, considering couplings between physical processes

The numerical model – Fig.4 – is based on a 3D and homogenized formulation of the conservation equations within the material. A porous medium can be characterized by several spatial scales, distinguishing between macroscopic scales (referred to as Darcy scale) and scales related to the material's morphology, grains, and pores. In a homogenization process, an intermediate scale is defined – small compared to macroscopic scales but large compared to pore-scale – called the Representative Elementary Volume (REV) scale.

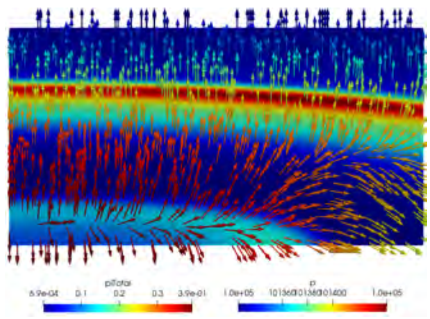

Figure 4 – *Pyrolysis front*

Volume-averaging homogenization theories are used to establish equations for averaged variables at the REV scale, incorporating the medium's heterogeneities.

These equations reveal effective properties dependent on local properties and morphology. Each gas is transported separately within the porous medium through diffusive and convective processes, originating from pyrolysis and heterogeneous reactions (smouldering). A general formulation of the reaction mechanism is adopted, accounting for detailed reaction schemes involving *"competitive"* and *"consecutive"* reactions. A pressure equation is solved, and gas velocity is calculated using Darcy's law. Energy is computed as the sensible enthalpy of the gas volume. Currently, the model assumes local thermal equilibrium, with gases passing through the material assumed to be at the same temperature as the condensed phases. Similarly, local compositional equilibrium is assumed, with heterogeneous reactions expressed in terms of averaged gaseous species concentrations rather than interface concentrations.

However, this work aims to implement smouldering-type reactions into the model, for which the two assumptions above are questionable. A two-temperature model will be developed to account for heat exchange between gas and condensed phases. The effect of the difference between the wall concentration and the average gas concentration on the smouldering reaction will also be studied. Finally, the last step will consider the ignition of a surface vegetation layer. The **PATO** model will be coupled with the **FireFOAM** solver from the **OpenFOAM** platform for gas-phase combustion calculations.

## 3. Conclusion and perpectives

This study will enhance the understanding of the physicochemical mechanisms governing the propagation of zombie fires. It will provide significant advances in preventing and combating these fires by offering predictive tools to anticipate their evolution and optimize extinction strategies.

## 4. Additional informations

- ☑ **Start of the contract :** Septembre 2025
- ☑ **Place :** ENSMA, Institut P' – UPR 3346 – CNRS, Poitiers, France
- ☑ **Salary :** 2300 euros gross / month
- ☑ **Contacts :**

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