Fire Dynamics: Understanding the Science of Fire

A foundational course in the physics, chemistry, and engineering principles that govern how fires ignite, grow, and spread.

What is Fire?

Fire is a **rapid chemical reaction** between a fuel and an oxidiser — typically oxygen — that releases significant energy as heat and light.

Core Equation: Fuel + Oxidiser → Products + Heat

Combustion is the broader scientific term, but fire specifically refers to a typically **uncontrolled** process involving a condensed fuel source — making its behaviour complex and potentially destructive.

A History Forged in Flames

1666

Great Fire of London — shaped early understanding of fire's destructive power across urban environments.

1871

Chicago Fire — reinforced lessons on fire spread through densely built cities and timber construction.

WWII

Bombing raids on Hamburg, Dresden, and Tokyo demonstrated the catastrophic potential of mass fires.

Present

WTC 9/11, Caracas Tower, and Wildland Urban Interface (WUI) fires continue to advance fire safety research.

The Physics and Chemistry of Fire Growth

Heat Release Rate (HRR)

The primary driver of fire growth. Growing fires are commonly modelled using the **t^2 (t-squared) power law**, where energy output rises with the square of time.

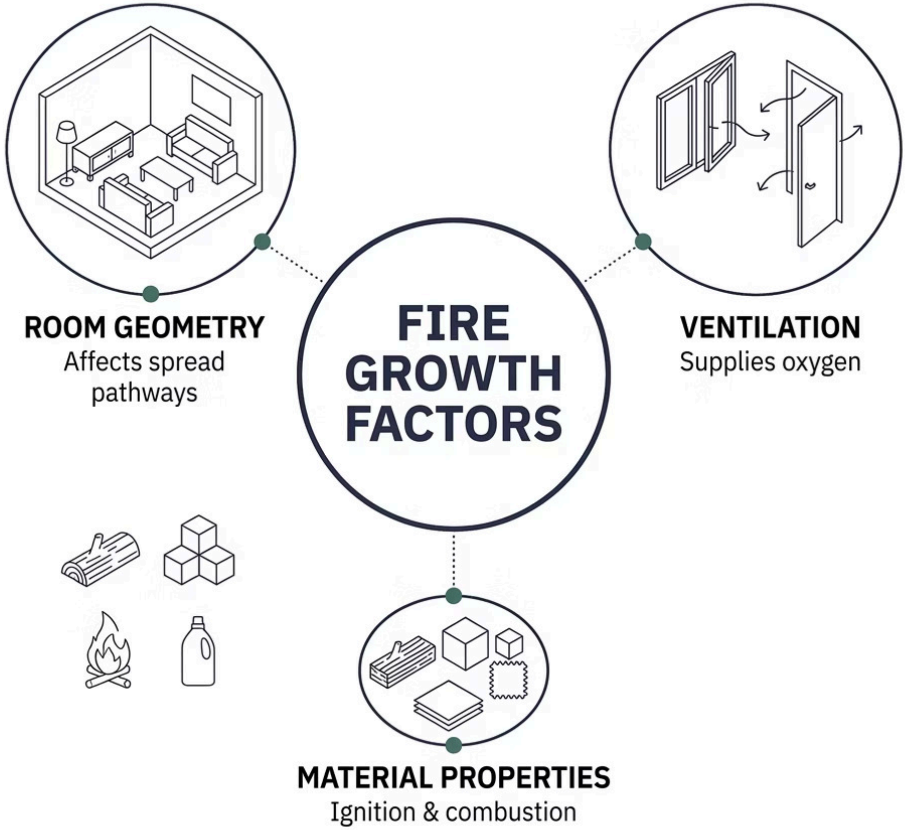
Key Physical Concepts

Practitioners must understand **flashpoint**, **flammable limits**, and heat transfer modes — **conduction**, **convection**, and **radiation**.

Fire Development Stages

From ignition through flame spread, fires may reach **flashover** — simultaneous involvement of all combustibles — or decay when fuel or oxygen becomes limited.

Factors Influencing Fire Growth



FIRE GROWTH FACTORS

ROOM GEOMETRY
Affects spread pathways

VENTILATION
Supplies oxygen

MATERIAL PROPERTIES
Ignition & combustion

Room & Contents Geometry

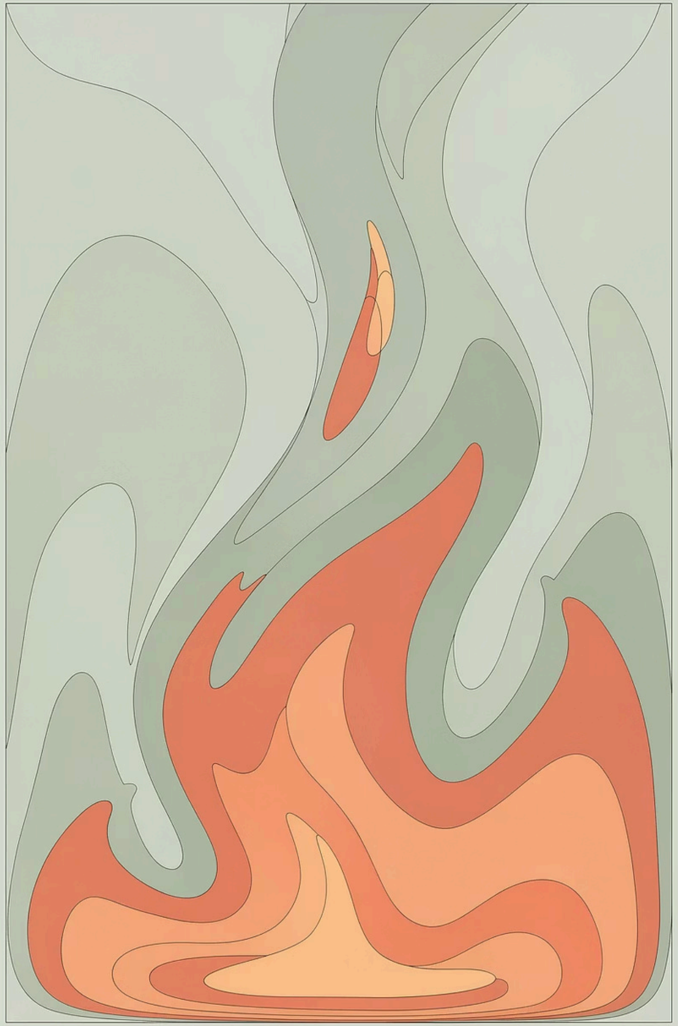
The shape, size, and arrangement of a space — including furniture and partitions — significantly influence how fire and hot gases spread.

Ventilation Factors

The availability and movement of air are critical. Poorly ventilated fires behave very differently from those with abundant oxygen supply.

Material Properties

Fuel type — wood, plastics, or textiles — dictates ignition temperature, burn rate, and peak heat release, fundamentally shaping fire behaviour.



From Laminar Flames to Complex Models

Laminar Flame Dynamics

The candle flame is a classic model for understanding fundamental combustion — buoyancy, diffusion, and heat feedback in their simplest form.

Dimensional Analysis

Blinov & Khudiakov's experimental data enables flame height prediction from heat release rate and pool dimensions — a powerful empirical tool.

Advanced Fire Modelling

RANS CFD and **Large Eddy Simulation (LES)** simulate turbulent fire behaviour in complex geometries, enabling detailed hazard prediction.

The Stages of Fire Growth

Ignition

Small localized flame, low HRR

Growth

Flame spreads, HRR rises (t-squared)

Flashover

All combustibles ignite, >600°C

Decay

Fuel or oxygen depleted, fire diminishes

Understanding these stages — from a small ignition source to potential flashover — is fundamental to predicting fire behaviour, designing effective suppression systems, and planning safe egress routes.

Tools for Fire Hazard Analysis (FHA)

The **US Nuclear Regulatory Commission (NRC)** developed **Fire Dynamics Tools (FDTs)** — a suite of Excel-based spreadsheet calculators for first-order fire hazard assessments in nuclear power plants.

These tools apply **empirical correlations** and established mathematical models drawn directly from fire dynamics principles, enabling engineers to perform rapid, structured calculations without full CFD modelling.

Excel–Based

Accessible, auditable first-order calculations

Empirical Basis

Grounded in validated fire science correlations

Nuclear Applications

Tailored for safety-critical facility assessments

The Importance of Understanding Limitations

Advanced models like CFD can capture broad fire behaviour — but **misuse carries serious risk**. Analyses related to the **Mont Blanc Tunnel Fire (1999)** demonstrated how incorrect model application can lead to dangerously flawed conclusions.

> No model is a substitute for deep understanding of the underlying fire science.

Practitioners must critically evaluate model assumptions, input sensitivity, and the physical validity of outputs at every stage of an assessment.

The Future of Fire Dynamics

→ Cutting-Edge Research

Ongoing work in **turbulence-chemistry interactions**, turbulence-radiation coupling, and two-phase flow continues to refine predictive accuracy.

→ Maturing Fire Engineering

The discipline demands practitioners who understand not just how to use tools, but **when and why** those tools are appropriate — and where they fall short.

→ Performance-Based Design

The ultimate goal: improving **risk-informed, performance-based fire protection engineering** through better education, better tools, and better professional judgement.