

NATO SPS MYP G6006

Workshop: Advanced Characterization of Acoustic Materials and Fire Performance Organized within
the framework of the NATO Science for Peace and Security Programme

Application of Advanced Computational Simulation Tools in Fire Safety Engineering

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Niš, 6 – 7 April 2026

FIRE DYNAMICS SIMULATOR - FDS

Fire Simulation Models

According to the room control volume, simulation models are classified into:

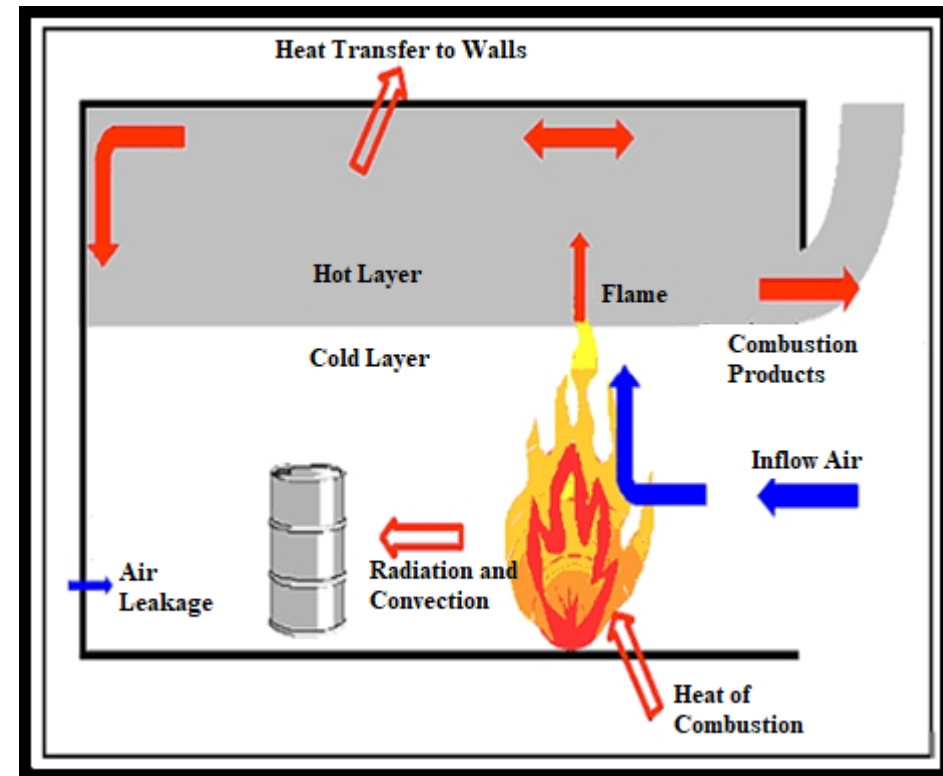
- *Zone models*
- *Field models*

Zone models

- Features / Characteristics:
- Two-layer approach (hot and cold layers);
- Simplified / Simple;
- Empirically based (derived from experimental research);
- Widely adopted / Broadly utilized;
- Applicable when a detailed spatial distribution of layer physical properties is not required;
- Limited potential for systemic improvement.

Most well-known models :

HAZARD I, BRI2, FIRM, ASET, FAST, CFAST.

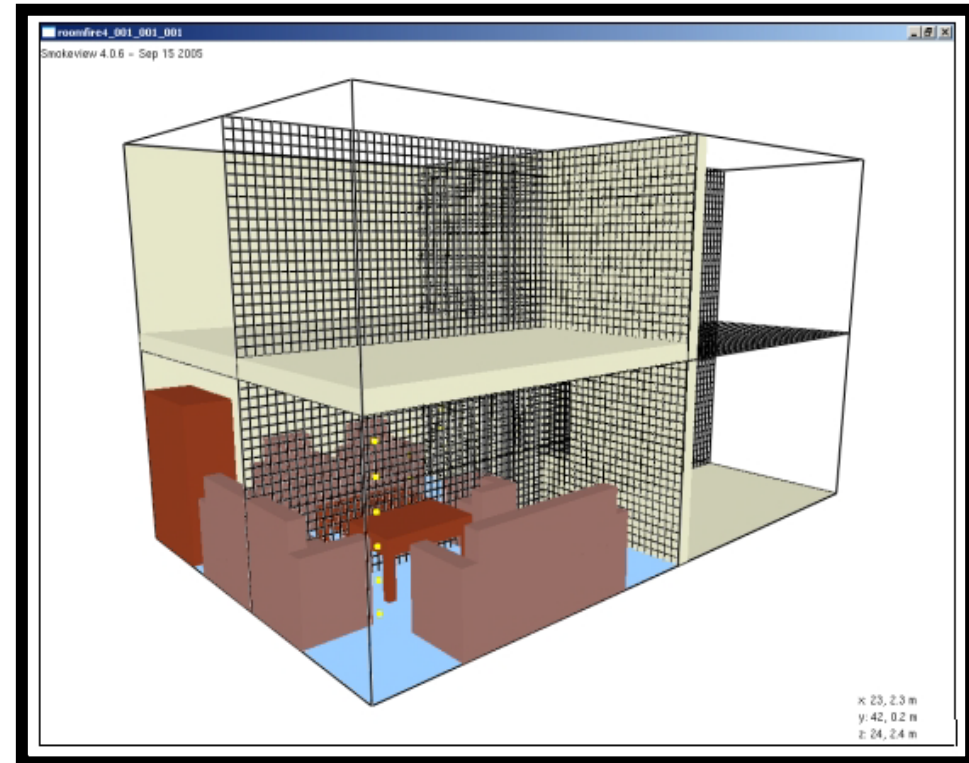


Field Models

- **Characteristics:**
- Based on **Computational Fluid Dynamics (CFD)**, i.e., on the application of the Reynolds-averaged conservation equations of mass (continuity), momentum, and energy within the *k-ε turbulence model*;
- Enable the modeling and analysis of fire phenomena in geometrically complex spaces;
- Limited by the averaging procedure applied to the governing equations of the model, as well as by computational resource constraints;
- Require the use of simplified combustion equations.

Most well-known models :

**PHOENICS, CFX, FLUENT,
JASMIN, KAMELEON, SMART-
FIRE, SOFIE, FDS.**



Hydrodynamic Model

- Solves the numerical form of the Navier-Stokes equations for low-speed, thermally-driven fluid flow (typically 10-20 m/s for fire scenarios).
- The core of the algorithm consists of an explicit predictor-corrector scheme.
- Turbulence is modeled using the Smagorinsky form for Large Eddy Simulation (LES).

Thermal Radiation Model

- Radiative heat transfer is described by the Radiative Transport Equation (RTE) for a non-scattering gray gas.
- These equations are solved using a technique analogous to the Finite Volume Method (FVM) for convective transport, employing approximately 100 independent solid angles.

Mixture Fraction Model

Combustion Modeling Based on Mesh Resolution:

- ❑ **Directly through a one-step finite-rate chemical reaction** (Applied in **DNS** computations where the mesh is sufficiently fine to resolve molecular diffusion between the fuel mass and oxygen);
- ❑ **Using a Mixture Fraction Model** (Applied in **LES** calculations, assuming that combustion is mixing-controlled, that reactions between oxygen and the fuel load are infinitely fast, and that the heat release rate is a function of oxygen consumption).

Ignition and Classification of Building Materials

- **Material Combustibility & Classification:** ASTM E 136, NFPA 259, EN 13501-1*;
- **Acoustic Materials:** Fire safety requirements and classification according to EN 13501-1;
- **Flame Spread (Walls & Ceilings):** ASTM E 84 and NFPA 265;
- **Flooring Radiant Panel Tests:** ASTM E 648 and NFPA 253;
- **Facade & Roofing Materials:** ASTM E 108, NFPA 268, and NFPA 285;
- **Wood-based Products:** ASTM E 136 and NFPA 259;
- **Fire Resistance of Structural Elements:** ASTM E 119 and ISO 834 (SRBS ISO 834).

Key Calorimetric Test Methods (Used for Classification):

- **Cone Calorimeter Method:** ISO 5660, ASTM E 1354 (Principles of Heat Release Rate);
- **Room/Corner Test:** ISO 9705.

Critical Heat Flux: 12.5 kW/m² - 14.7 kW/m²

* EN 13501-1: Euroclass Classification System

The classification is based on three critical parameters: **Reaction to Fire**, **Smoke Production**, and **Flaming Droplets**.

1. Main Classification: Reaction to Fire (A1 – F)

- **A1, A2:** Non-combustible materials (e.g., concrete, stone wool);
- **B, C:** Limited contribution to fire (e.g., high-quality acoustic panels);
- **D, E:** Medium to high contribution to fire (e.g., wood-based products);
- **F:** Easily flammable or untested materials.

2. Smoke Production (s1 – s3)

- **s1:** Little or no smoke production (Best performance);
- **s2:** Medium smoke production;
- **s3:** Substantial smoke production (Worst performance).

3. Flaming Droplets/Particles (d0 – d2)

- **d0:** No flaming droplets or particles (Best performance);
- **d1:** Droplets persist for less than 10 seconds;
- **d2:** Frequent or persistent flaming droplets (Worst performance).

Thermal inertia ($k\rho c$) and ignition temperature values for selected materials

Material	Tig (°C)	$k\rho c$ (kW ² s/m ⁴ K ²)
Lexan	744	0.68
Fire-retardant plywood	620	0.76
Carpet (Nylon/Wool)	412	0.68
PMMA (1.59mm)	278	0.73

Ignition Time vs. Incident Heat Flux

Incident Heat Flux (kW/m ²)	Wood board (thermally thin)	Spruce (thermally thick)	PVC 3mm (grey)	PVC 5mm (pressed, white)
50	40	15	26	55
40	58	30	43	95
30	82	60	71	209
20	166	625	184	332
15	400	~1200	655	858
10	no ignition	no ignition	no ignition	no ignition

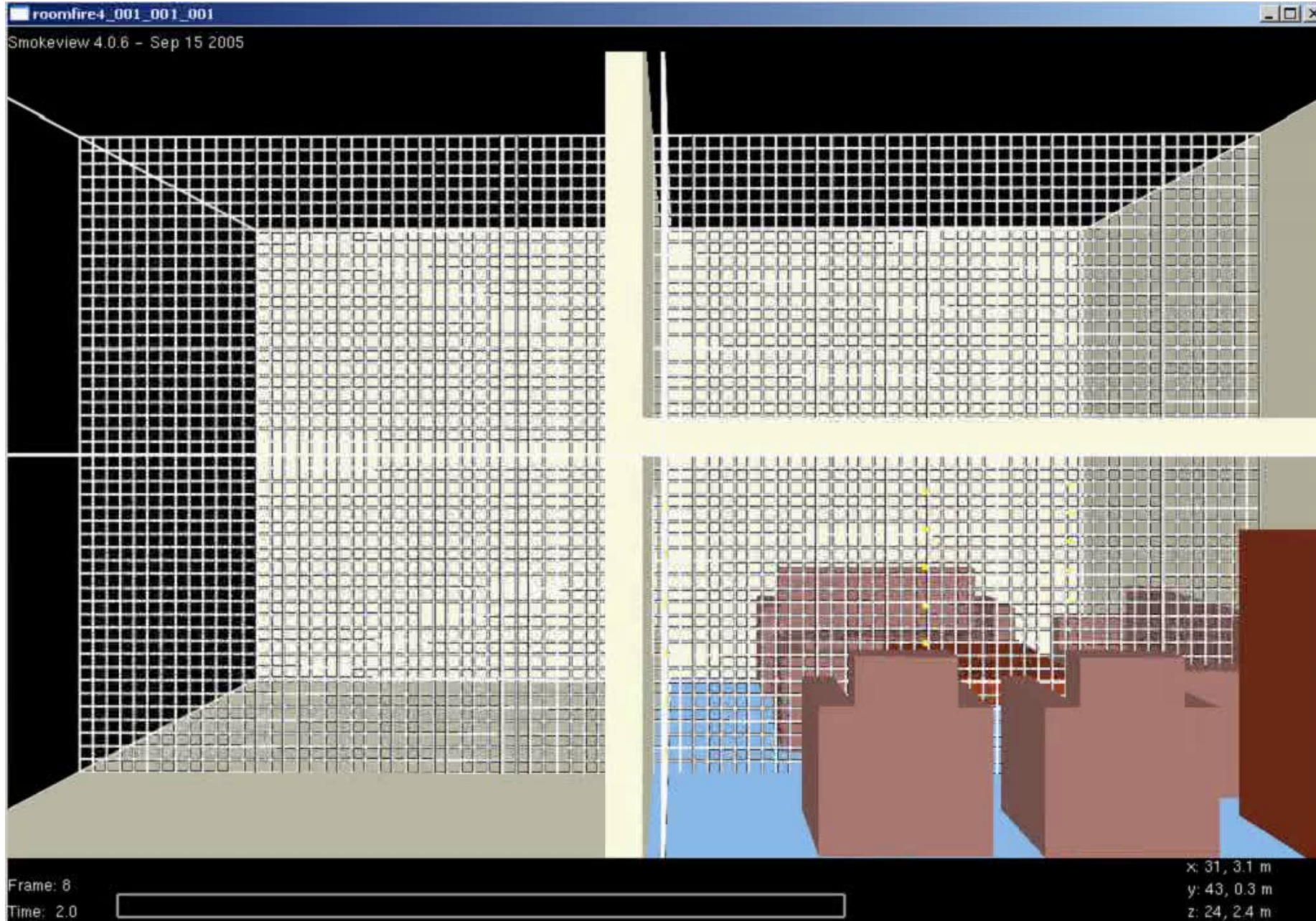
Influence of surface coating (painting) on the critical heat flux level

Test Method	Unpainted surface (kW/m ²)	Painted surface (kW/m ²)
Large-scale test	18-19	26-30
Laboratory test	10	15

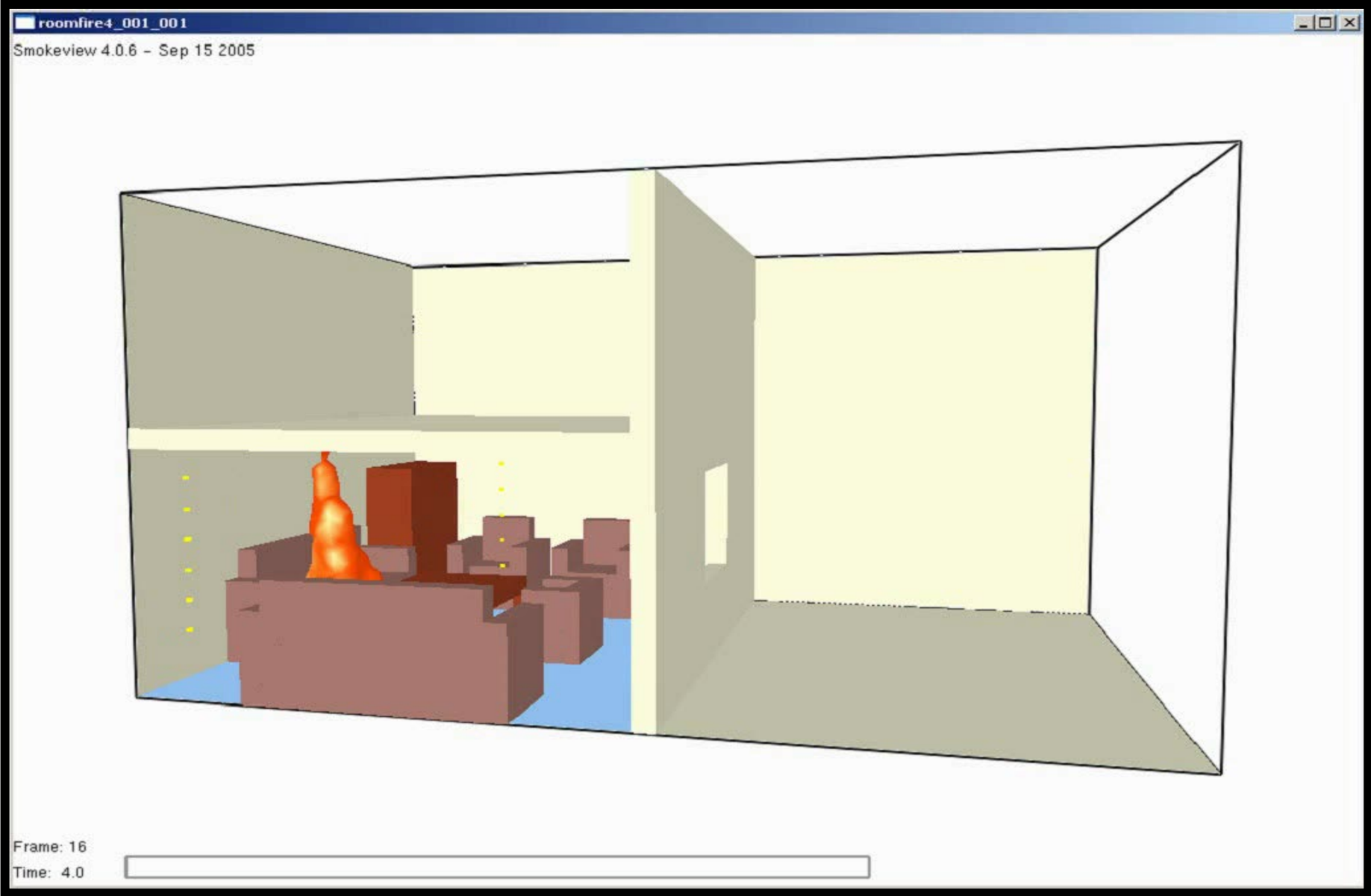
Ignition time (t_{ig}) for textile samples as a function of incident heat flux

Incident Heat Flux (kW/m ²)	Cotton	Cotton (FR)	Polyester/Cotton (65/35)	Polyester/Cotton (50/50)
198	2	3	3	6
118	4	7	8	15
87	6	12	15	26
70	8	19	26	43
52	13	41	no ignition	no ignition

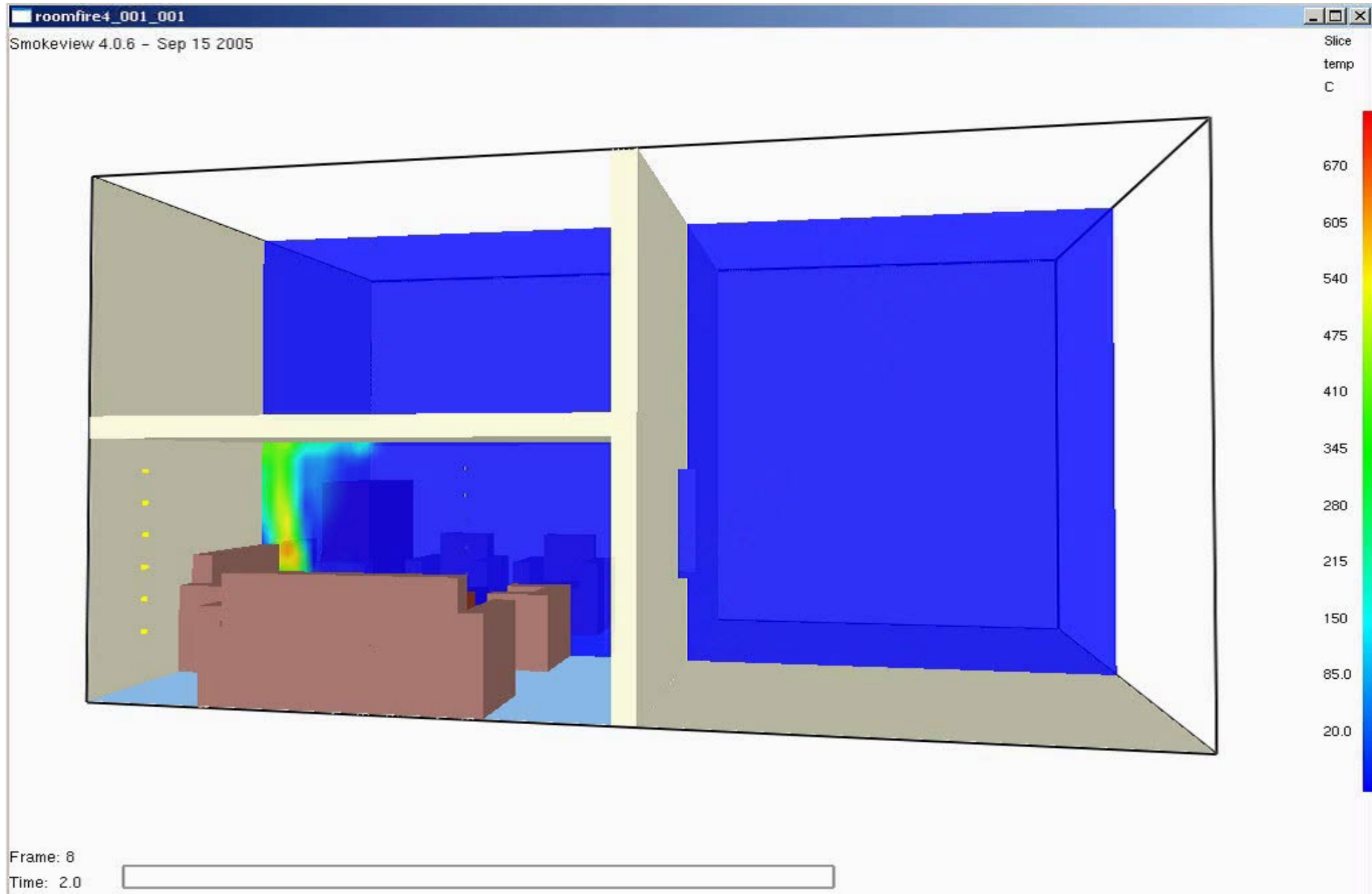
Computational Grid Configuration



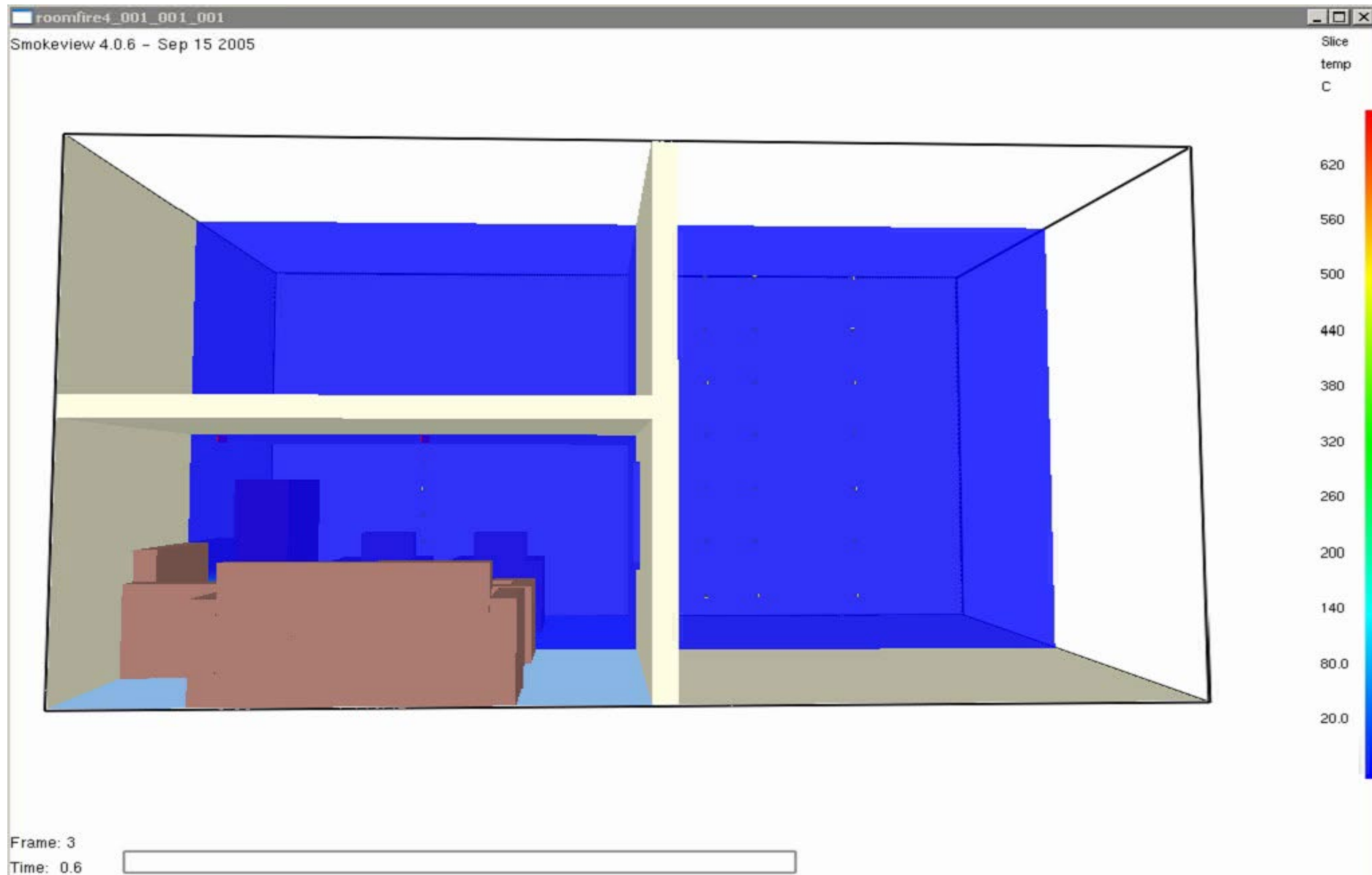
Fire Development



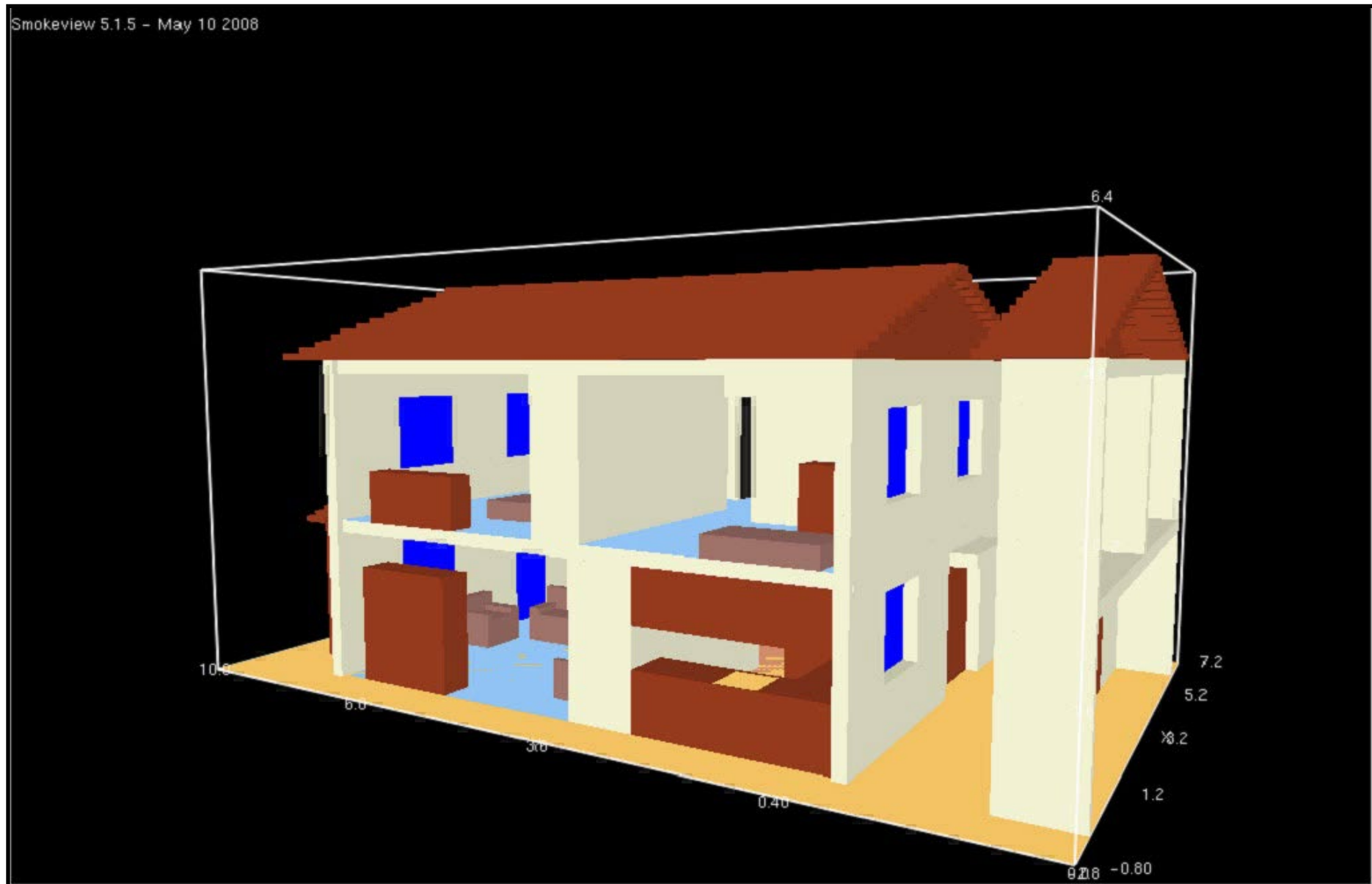
Temperature Distribution in a Vertical Plane



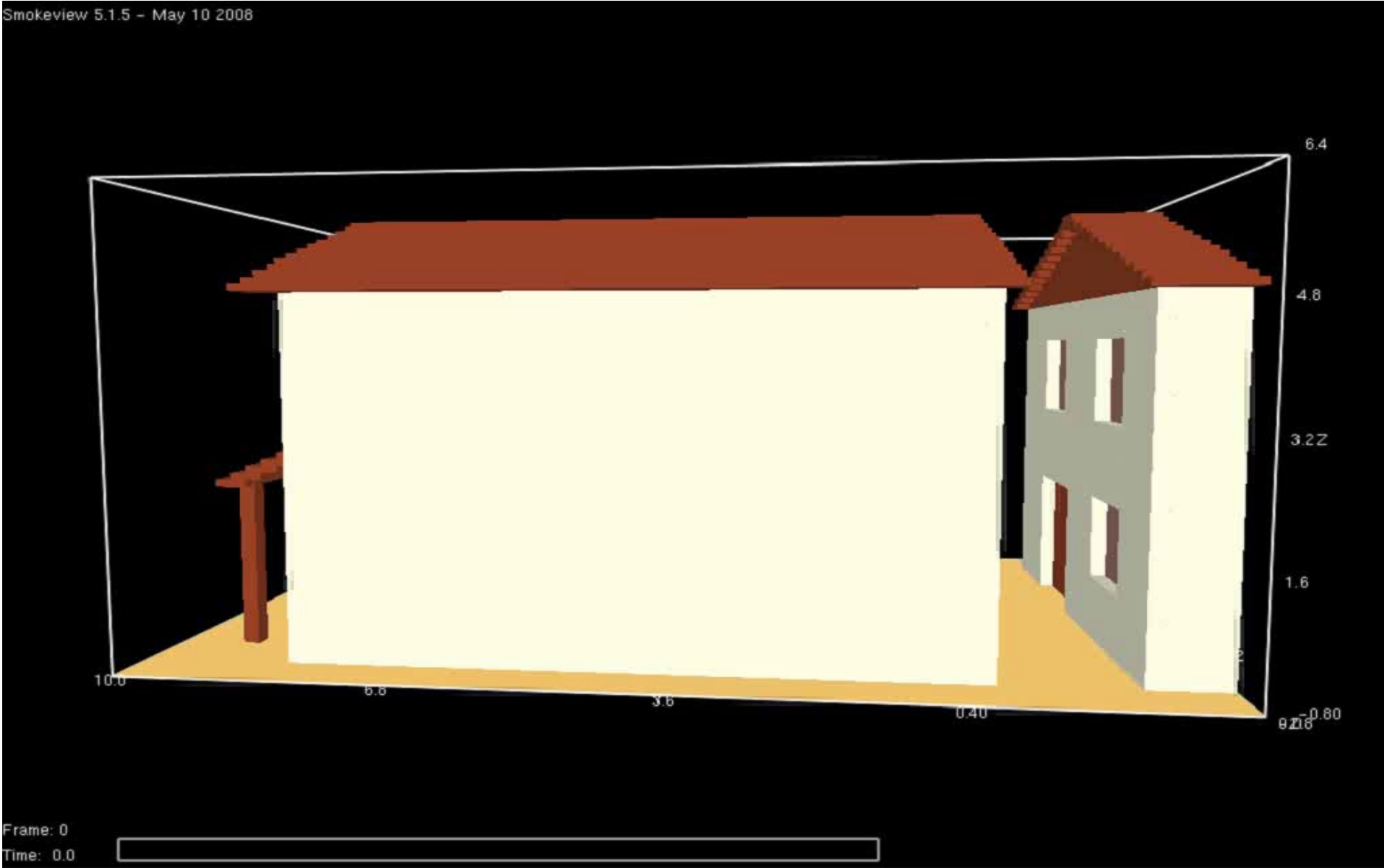
Simulation of Sprinkler System Operation



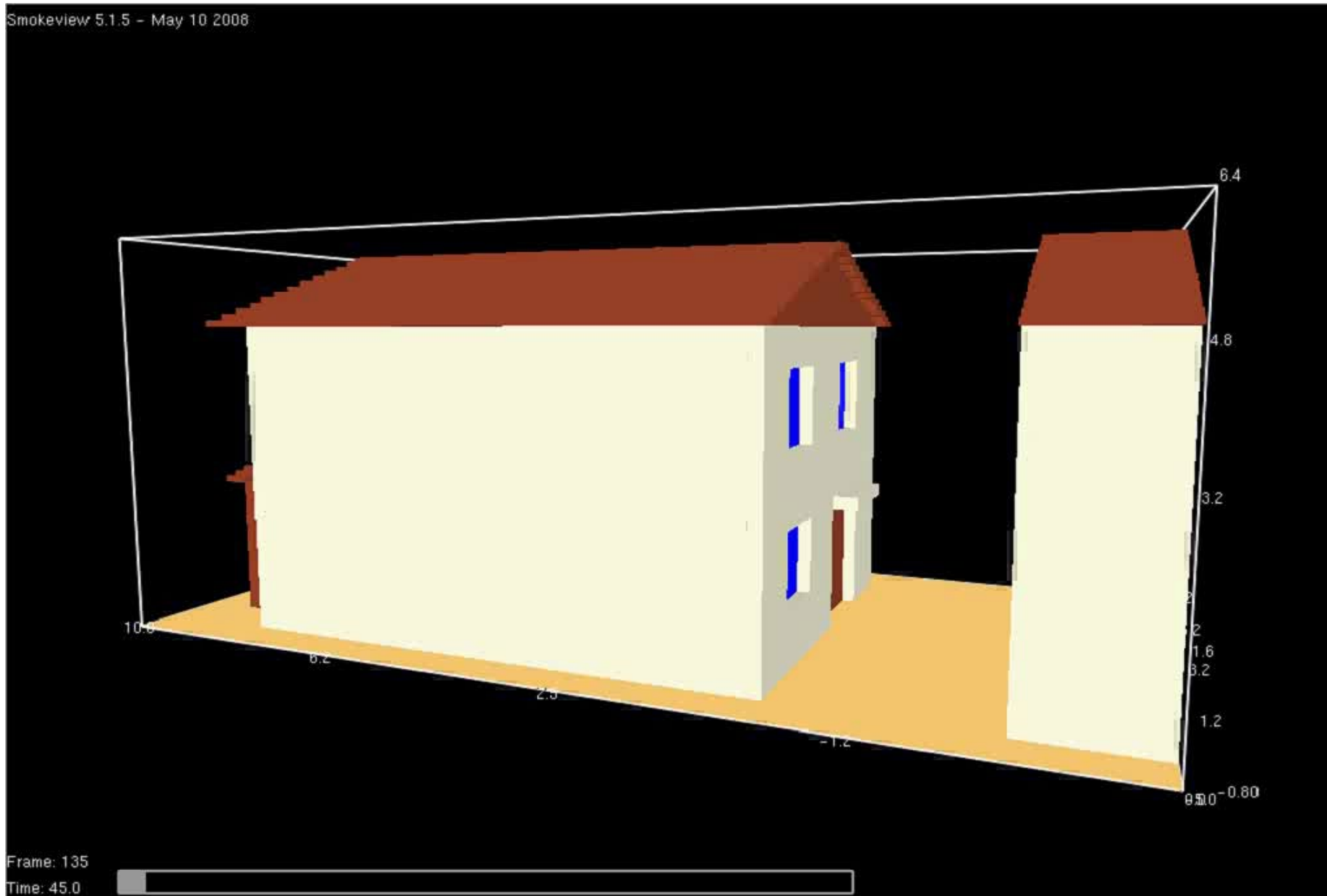
Application of Fire Dynamics Simulator in the Verification of Permissible Separation Distances Between Structures



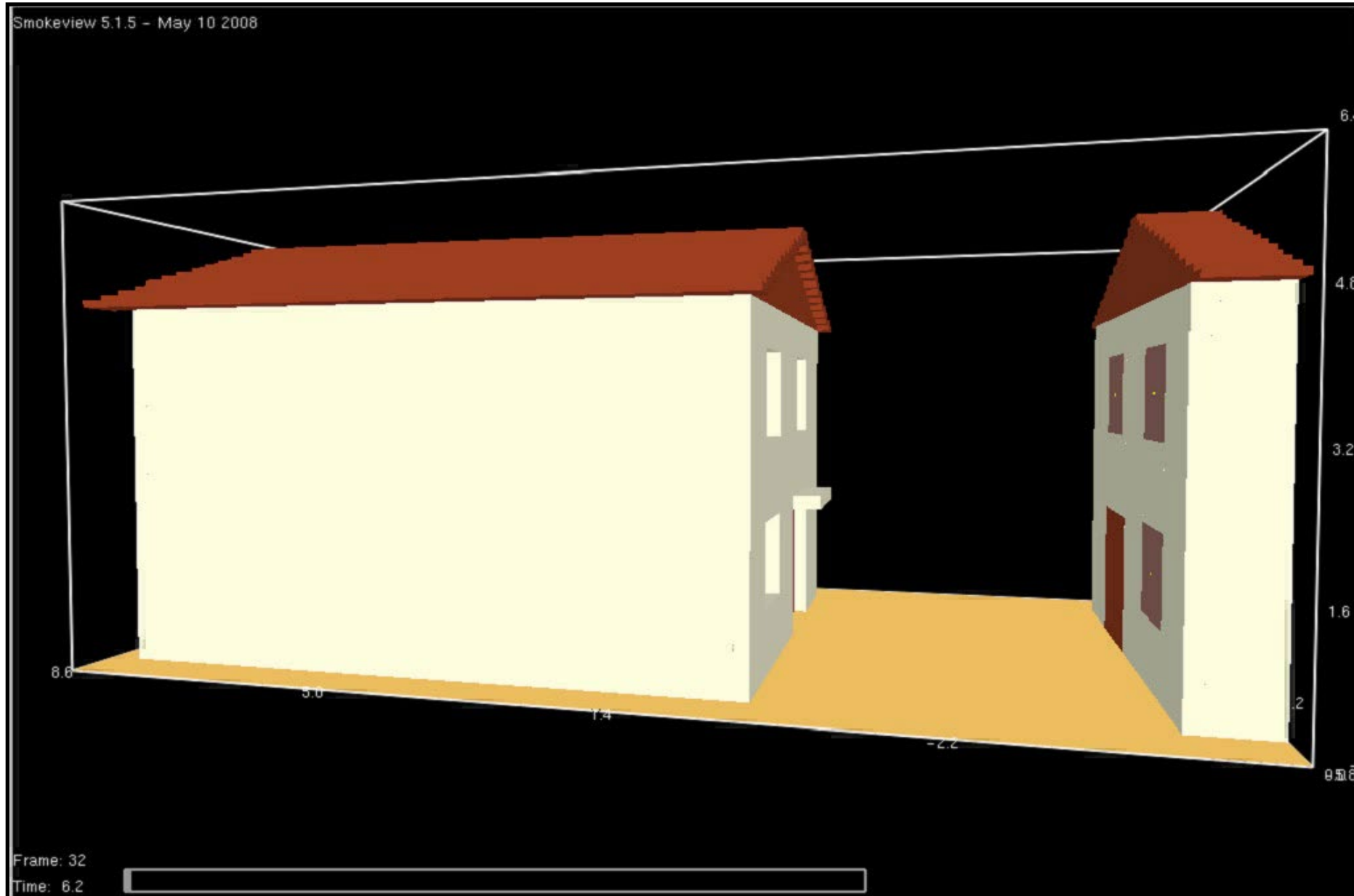
Separation distance between structures: 2 meters



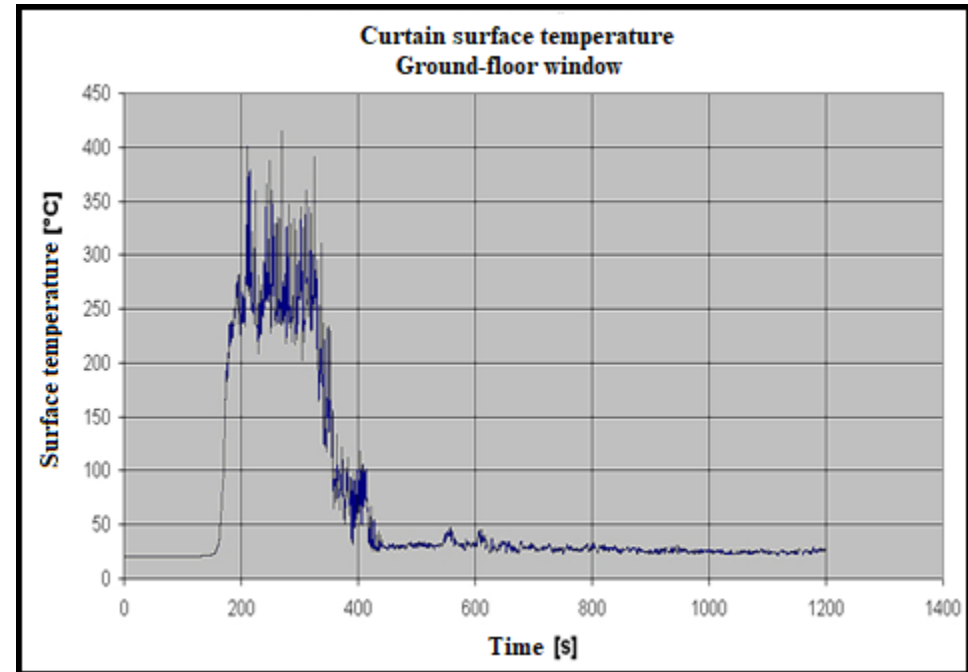
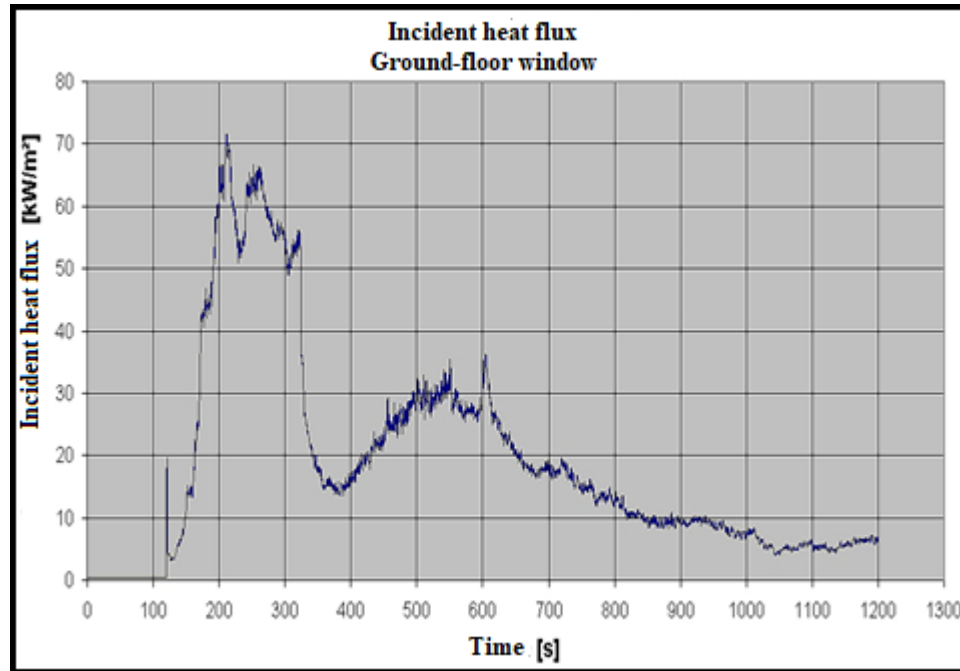
Separation distance between structures: 3.2 meters



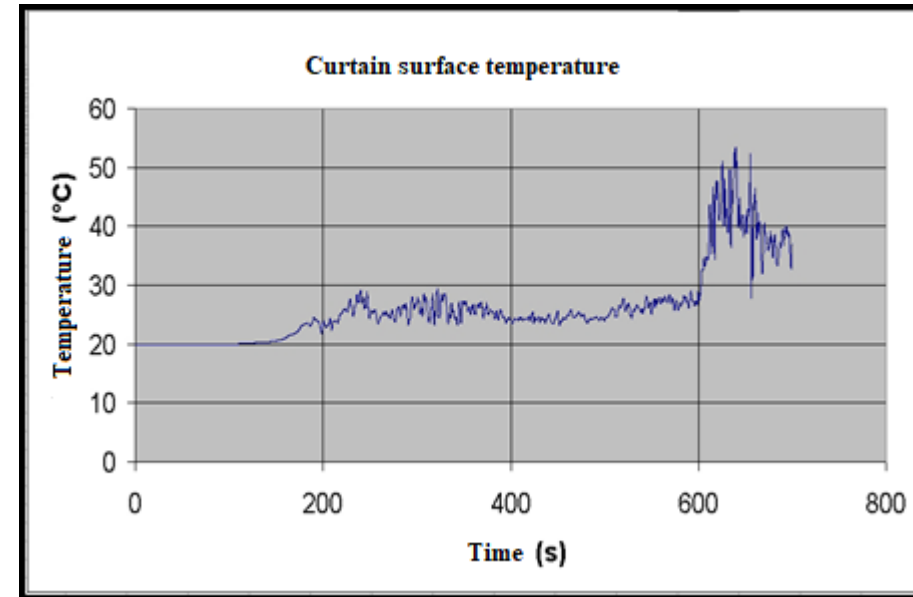
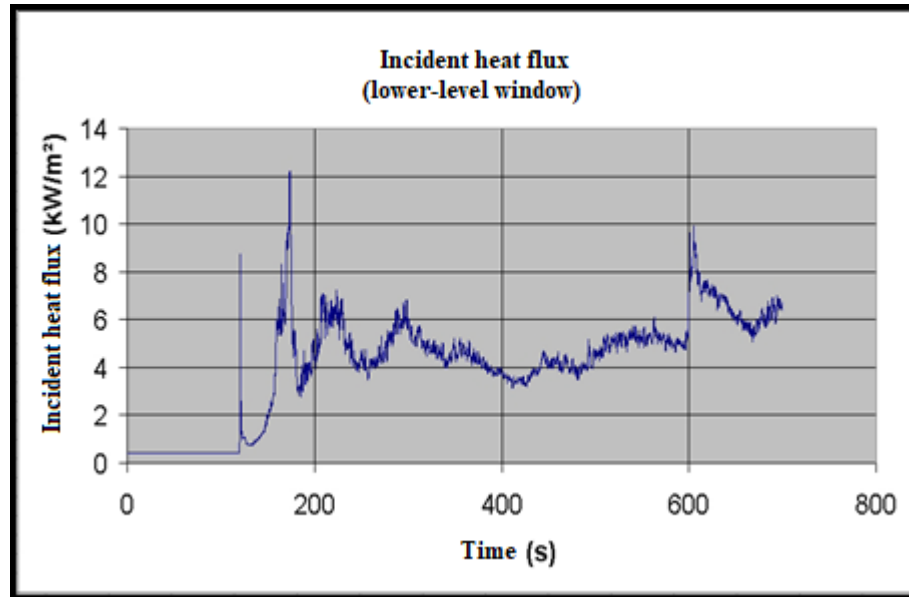
Separation distance between structures: 4.8 meters



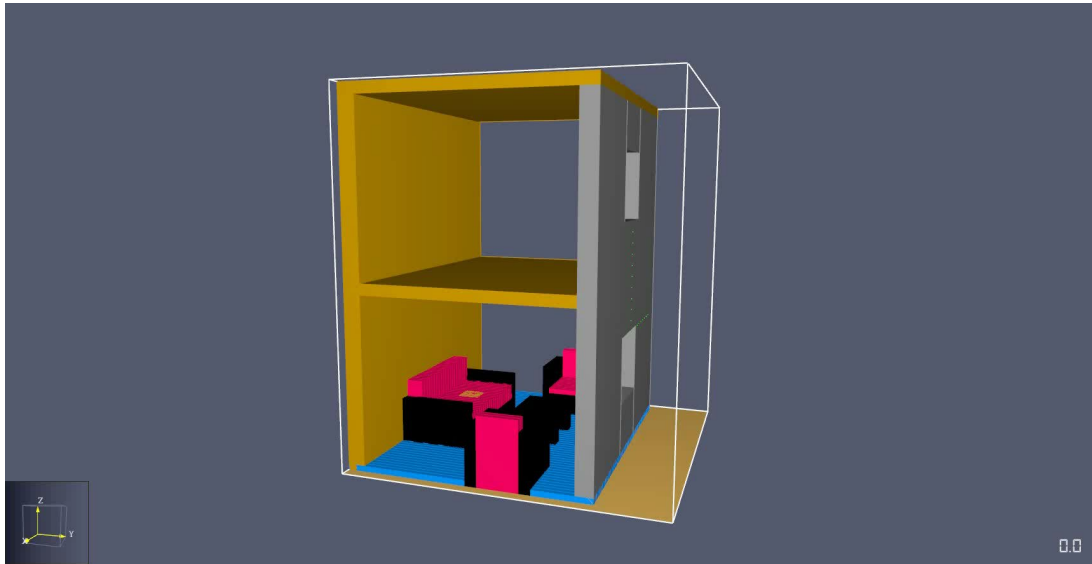
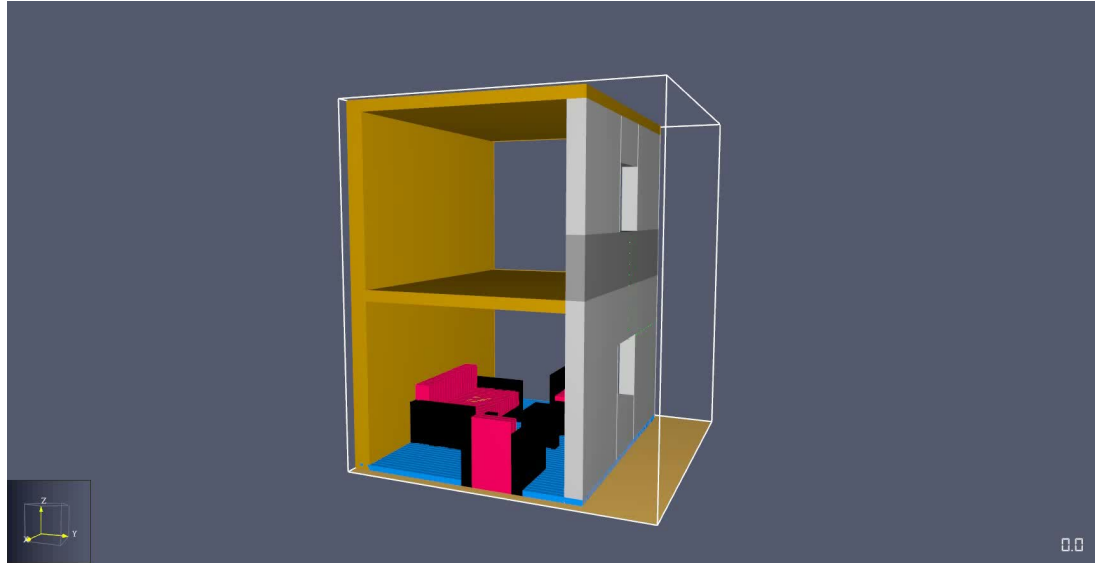
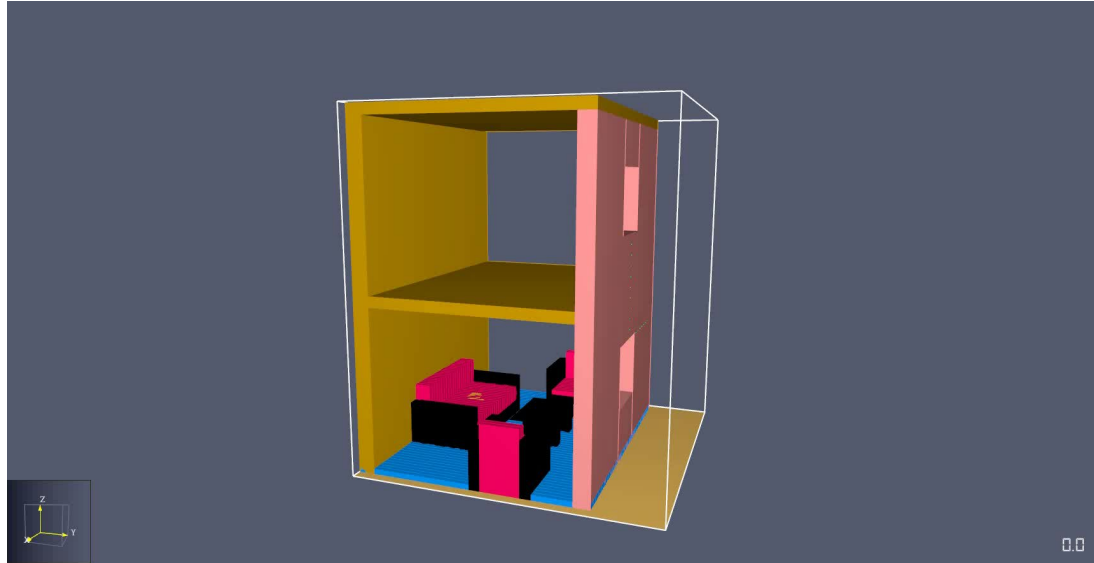
Incident heat flux and surface temperature of a curtain (lower window of an adjacent building) for a scenario with a 3.2-meter separation distance between the objects.



Incident heat flux and curtain surface temperature (lower-level window of the adjacent building) for a 4.8-meter separation distance scenario



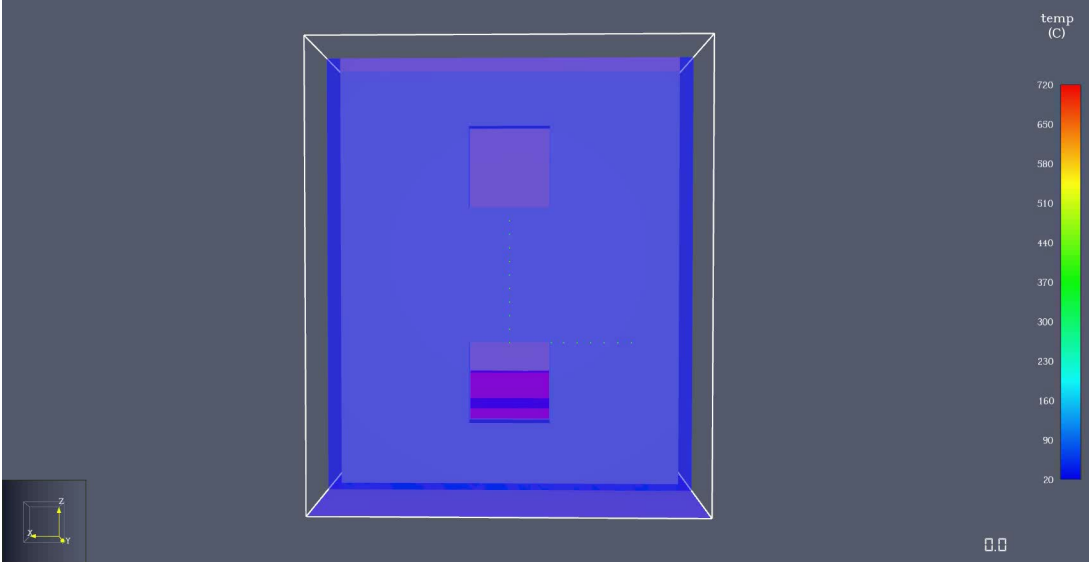
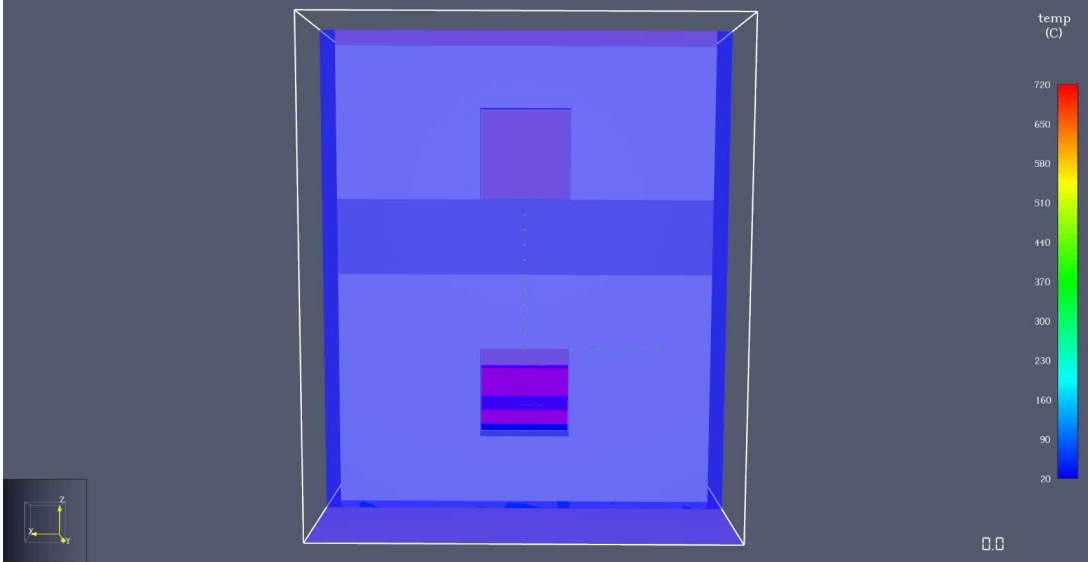
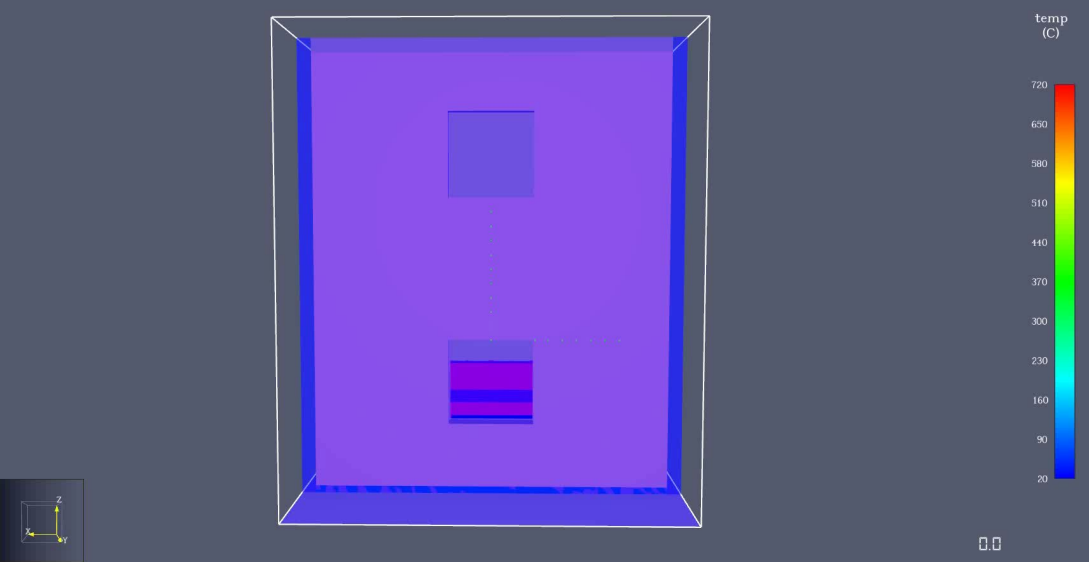
Heating of thermal insulation materials caused by a compartment fire (Fire development)



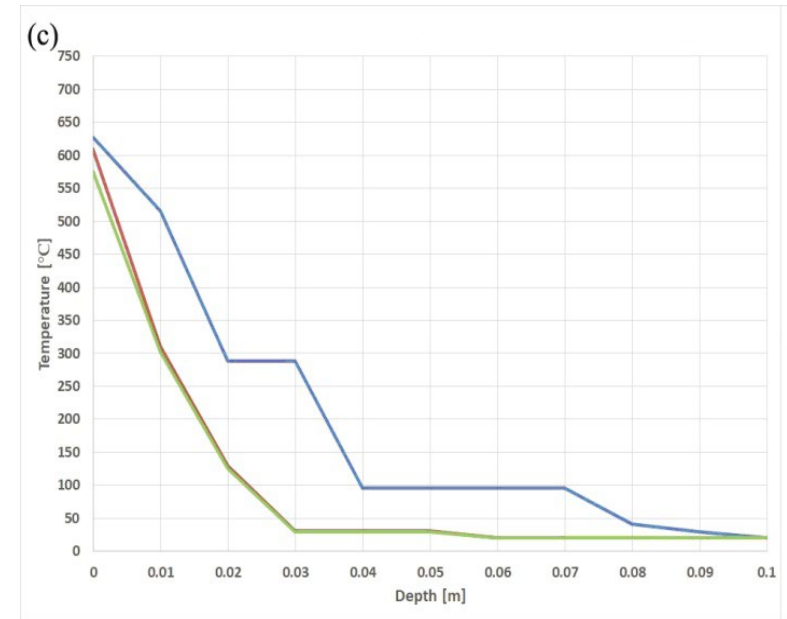
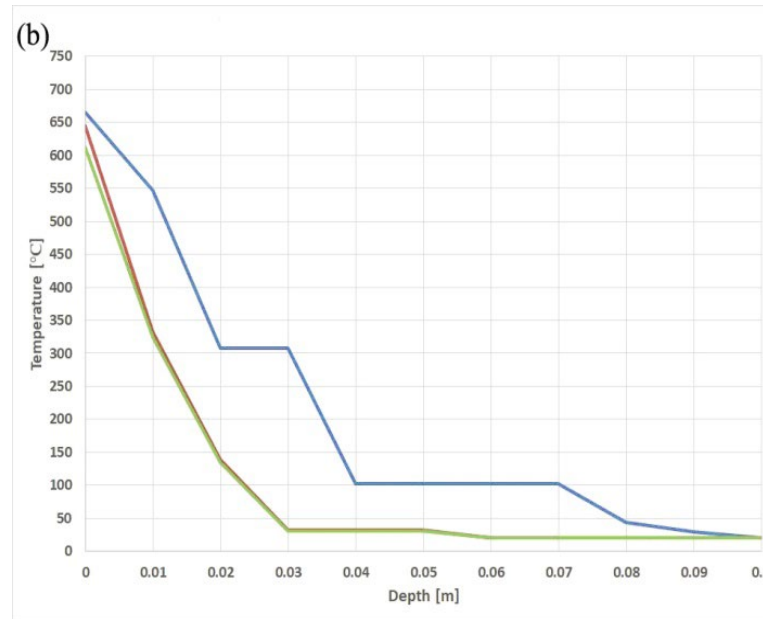
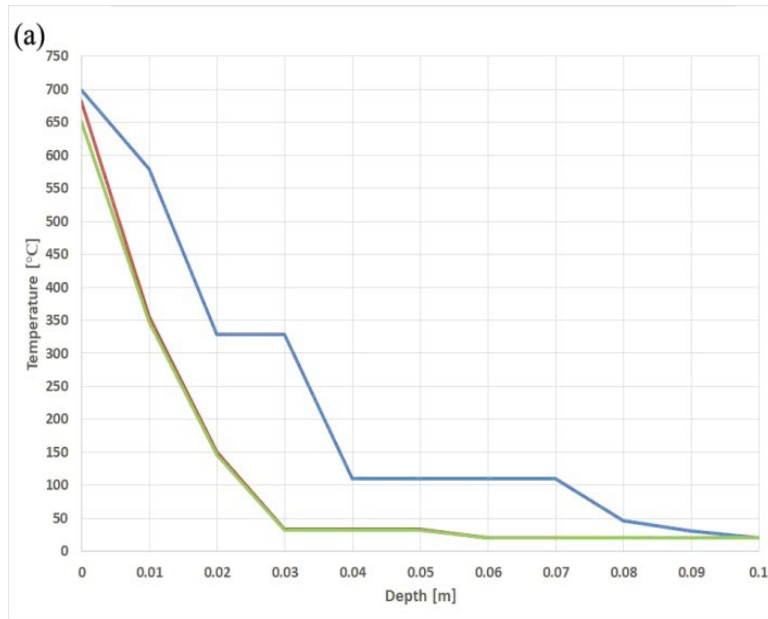
Thermodynamic properties of the building insulation materials and their appropriate fire reaction class according to the standard SRPS EN 13501-1 are shown in Table

Property	Expanded polystyrene	Stone wool
Thickness, m	0.1	0.1
Density, kg/m ³	20	160
Thermal conductivity, W/mK	0.03	0.04
Specific heat capacity, J/kgK	650	1260
Ignition temperature, °C	370	-
Reaction to fire - classification	B-s2, d0	A2-s1, d0

Heating of thermal insulation materials caused by a compartment fire (Façade temperature)

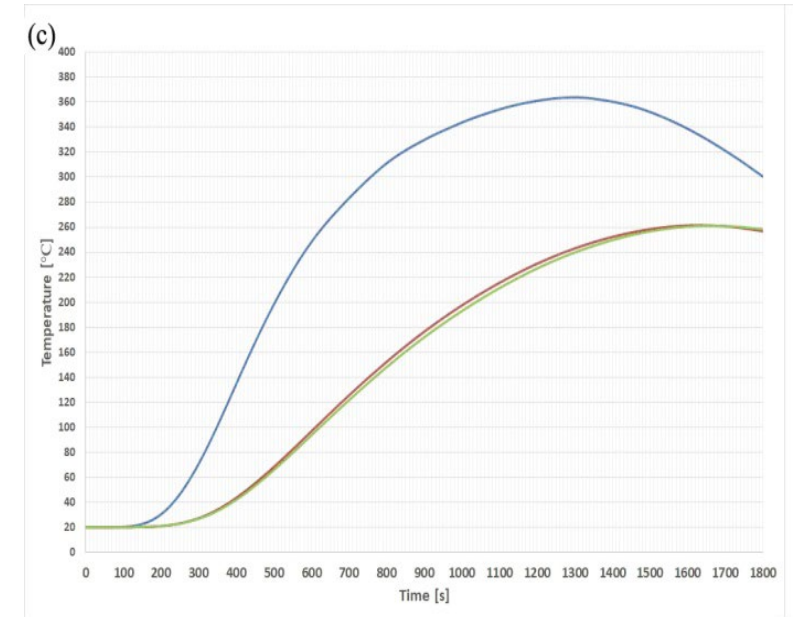
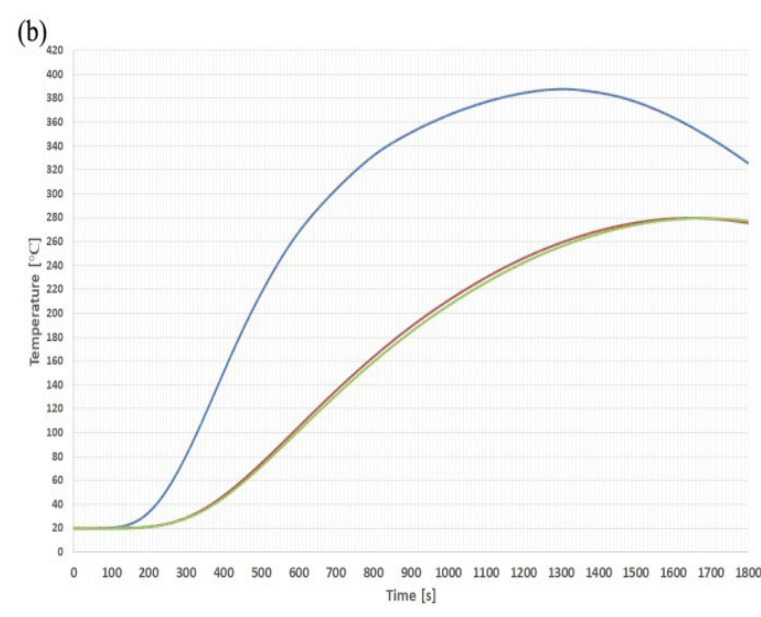
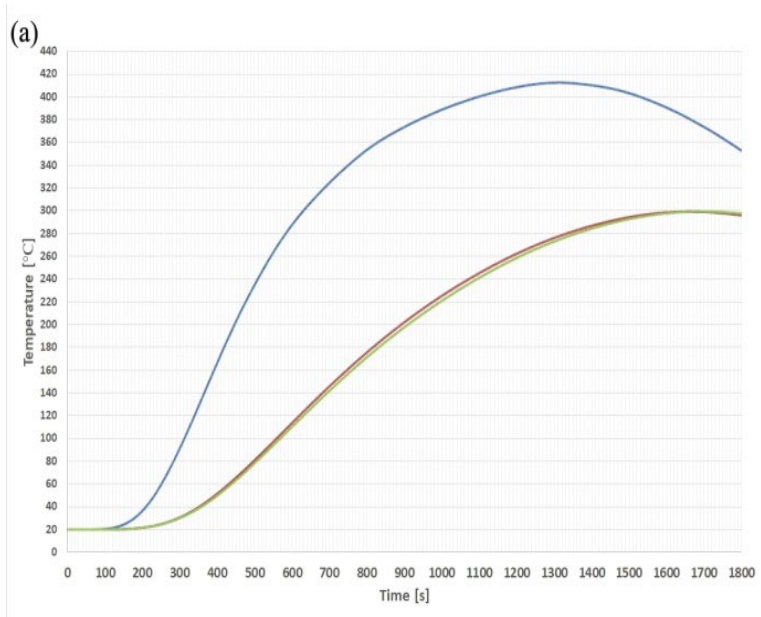


Temperature through facade in 713 s at: (a) 0.4 m; (b) 0.6 m; (c) 0.8 m



— - expanded polystyrene; — - expanded polystyrene and stone wool; — - stone wool

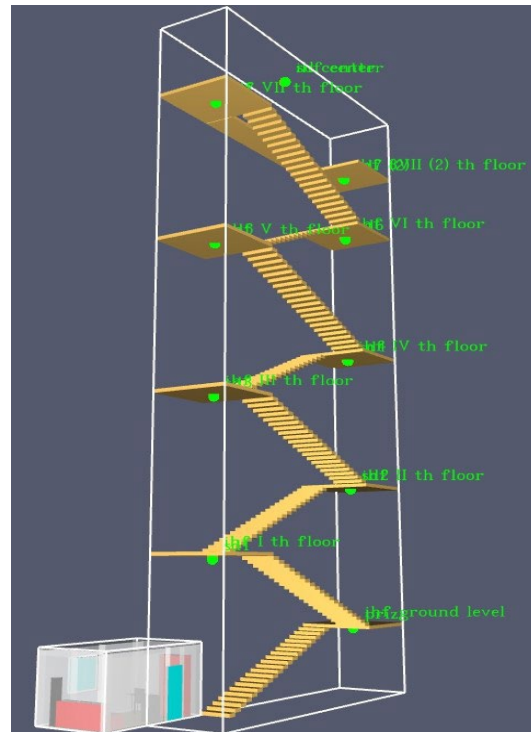
Time-averaged temperature inside facade in a depth of 2 cm: (a) 0.4 m; (b) 0.6 m; (c) 0.8 m



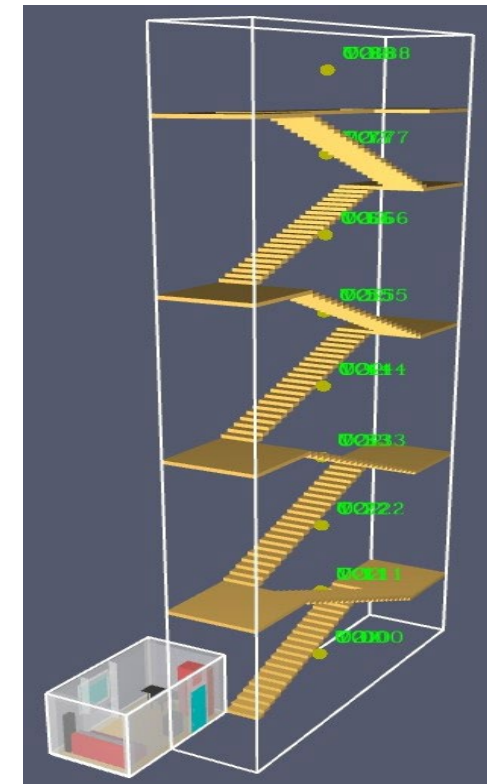
— - expanded polystyrene; — - expanded polystyrene and stone wool; — - stone wool

Application of Fire Dynamics Simulator in the Optimization of Smoke Detector Placement in the Stairwell of a High-Rise Building

Smoke detectors are installed at the top of each landing, positioned 1.5 m away from the stairs (in accordance with the British standard) at the center of the ceiling, while visibility, temperature, and gas concentration sensors (CO, CO₂, and O₂) are located in the central part of the stairwell with vertical spacings of 3 m.

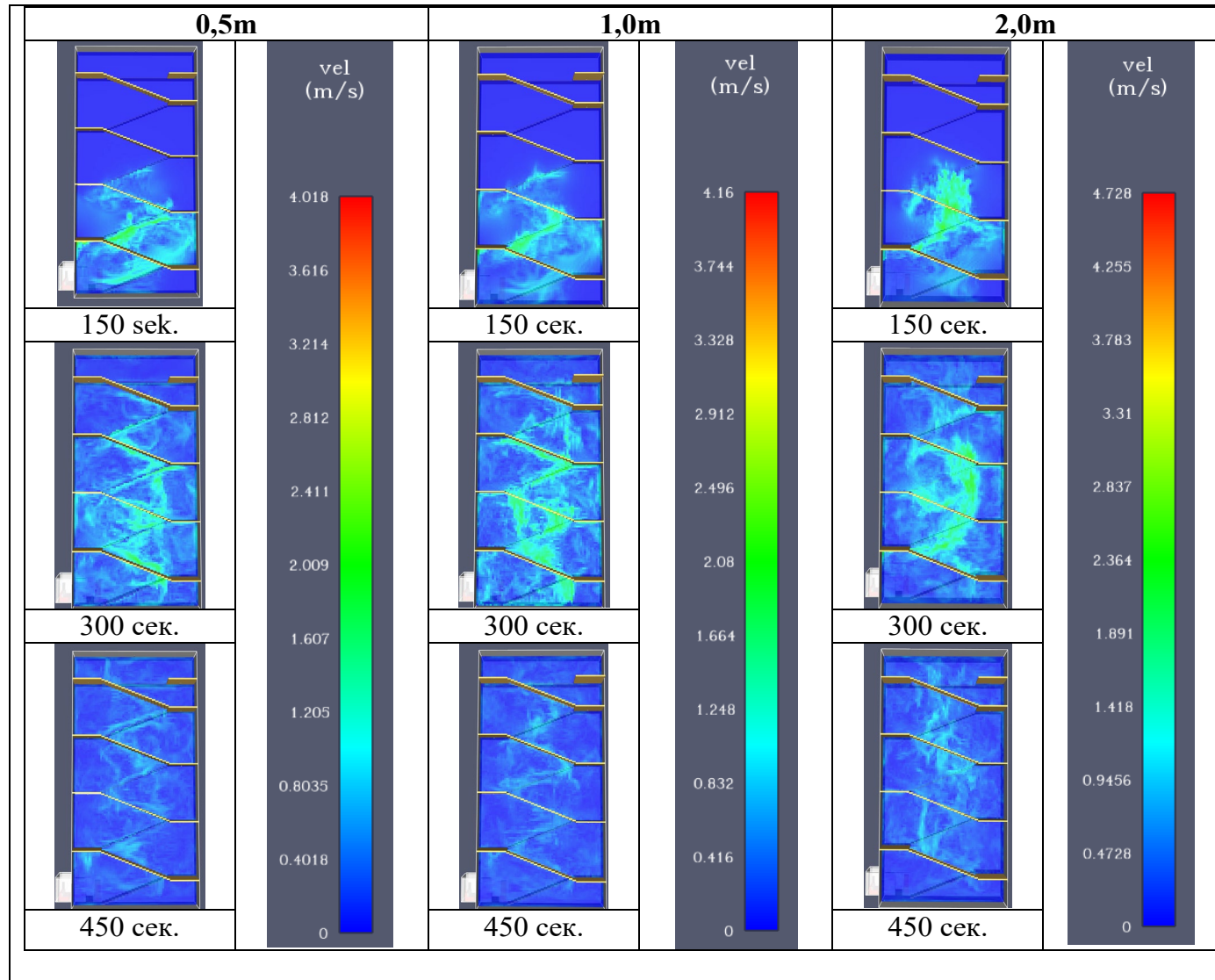


Smoke Detector Layout

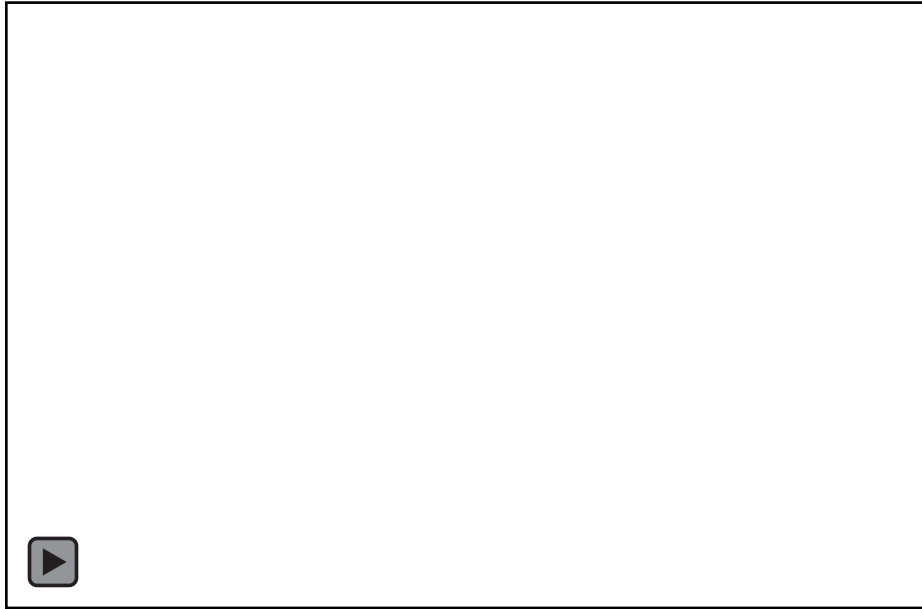


Sensor Layout

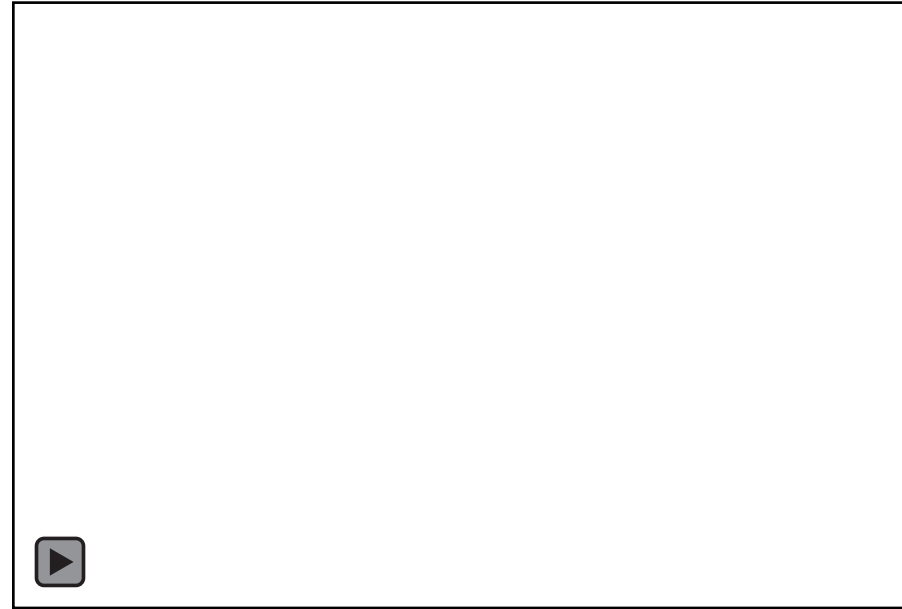
Flow Velocity of Combustion Products in the Stairwell



Fire Development at 0.5 m, 1.0 m, and 2 m



0.5 m

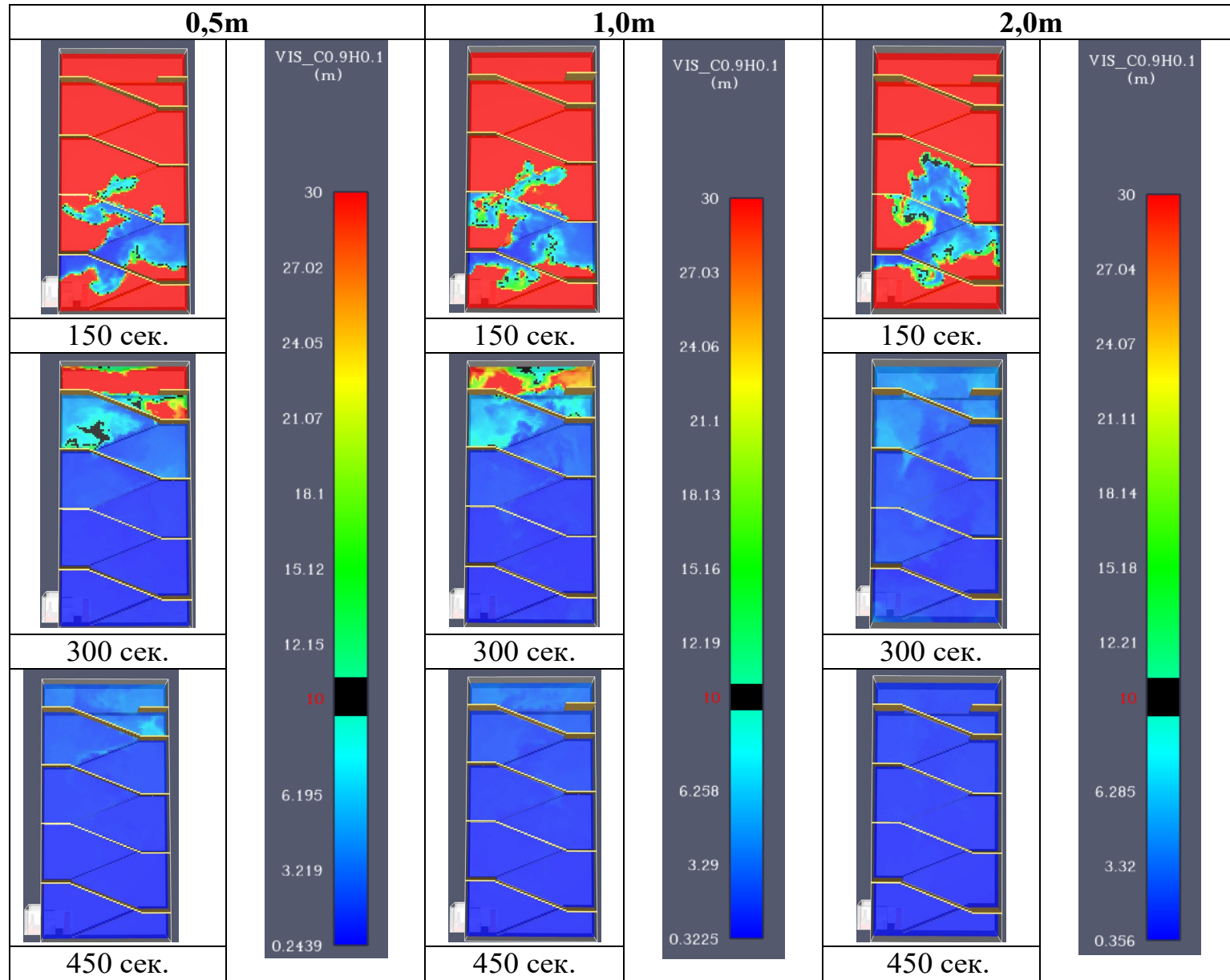


1 m



2 m

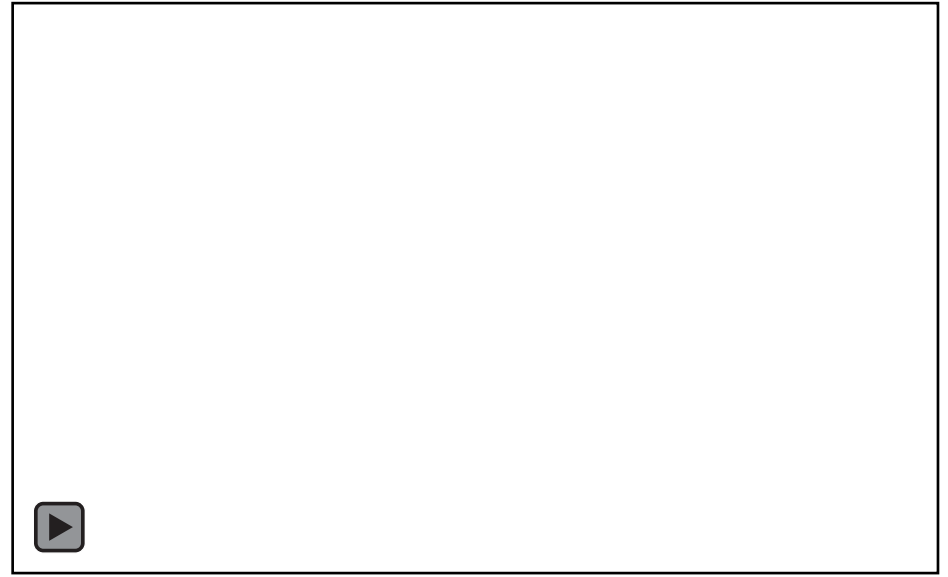
Smoke Visibility in the Stairwell



Smoke Visibility at 0.5 m, 1 m, and 2 m



0.5 m

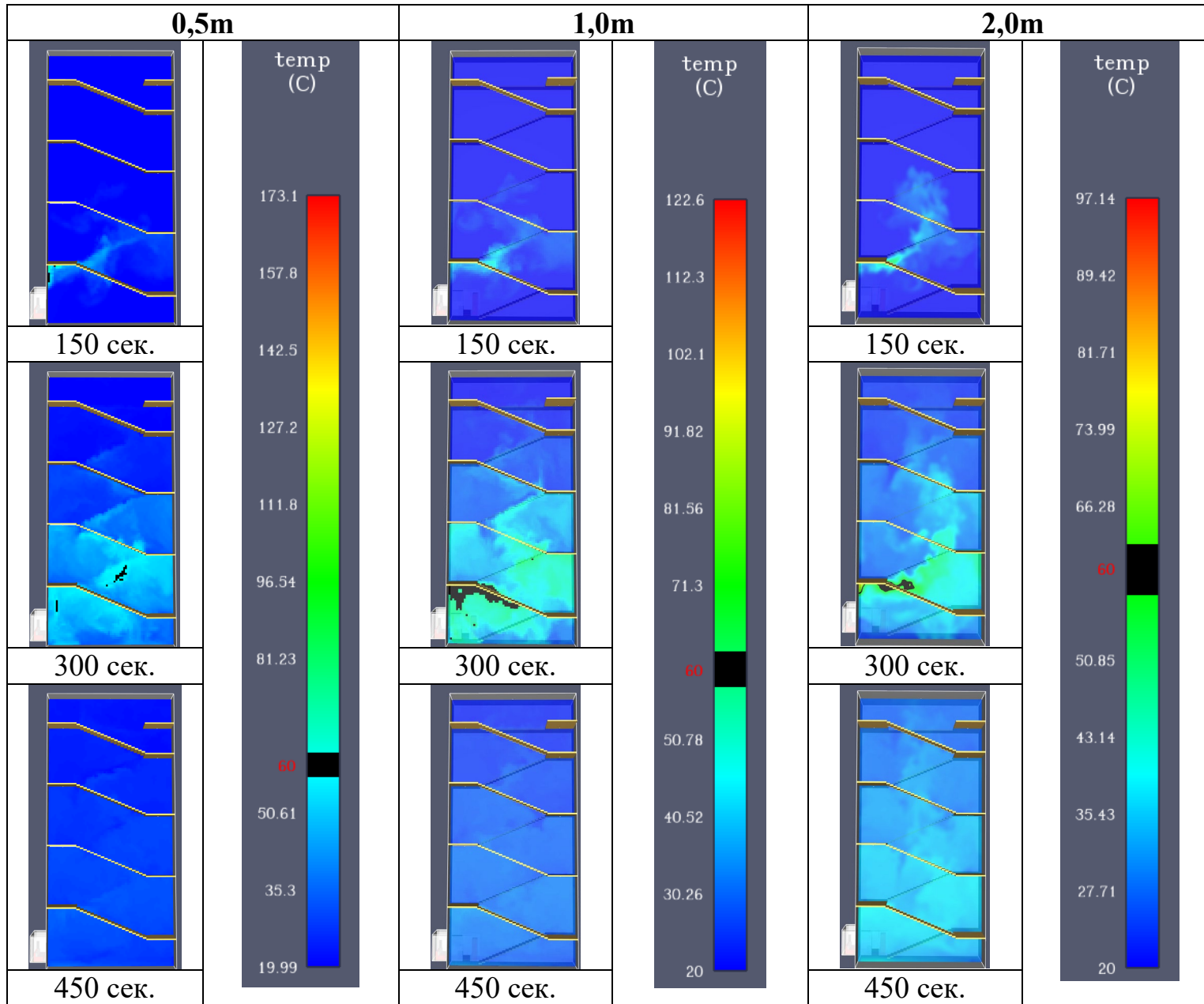


1 m

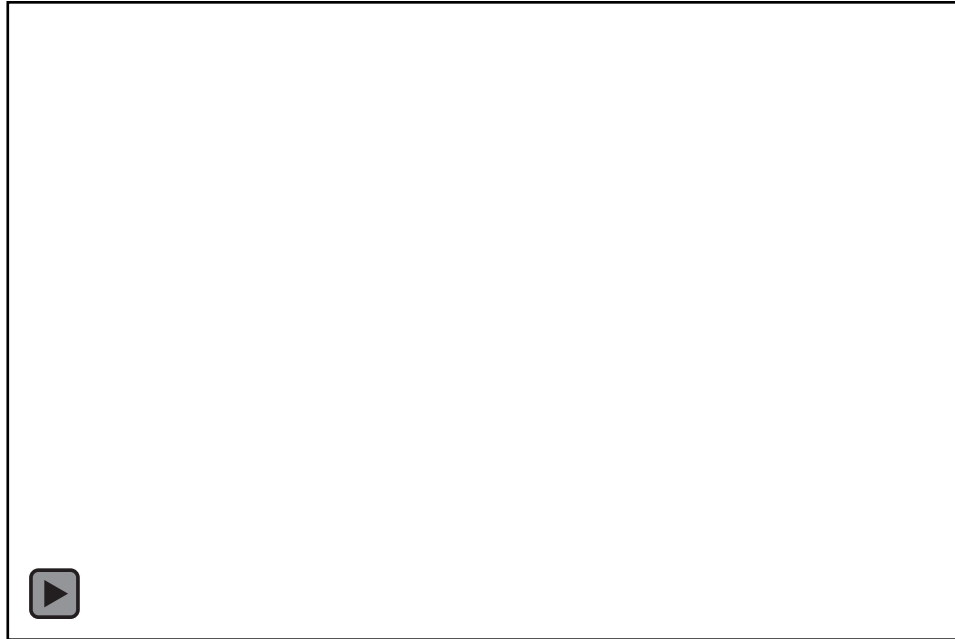


2 m

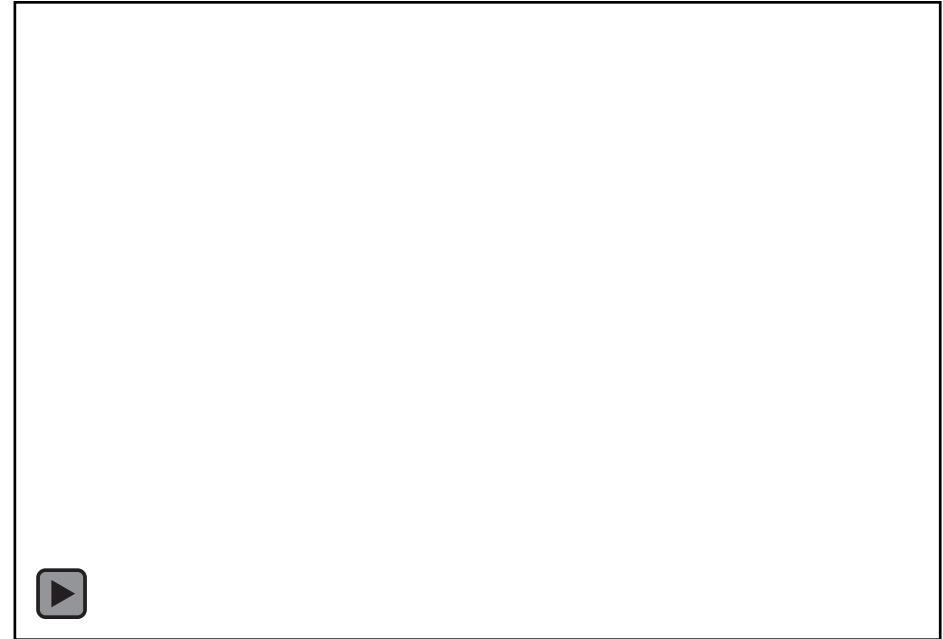
Temperature in the Stairwell



CO Concentration at 0.5 m, 1 m, and 2 m [ppm × 10]



0.5 m

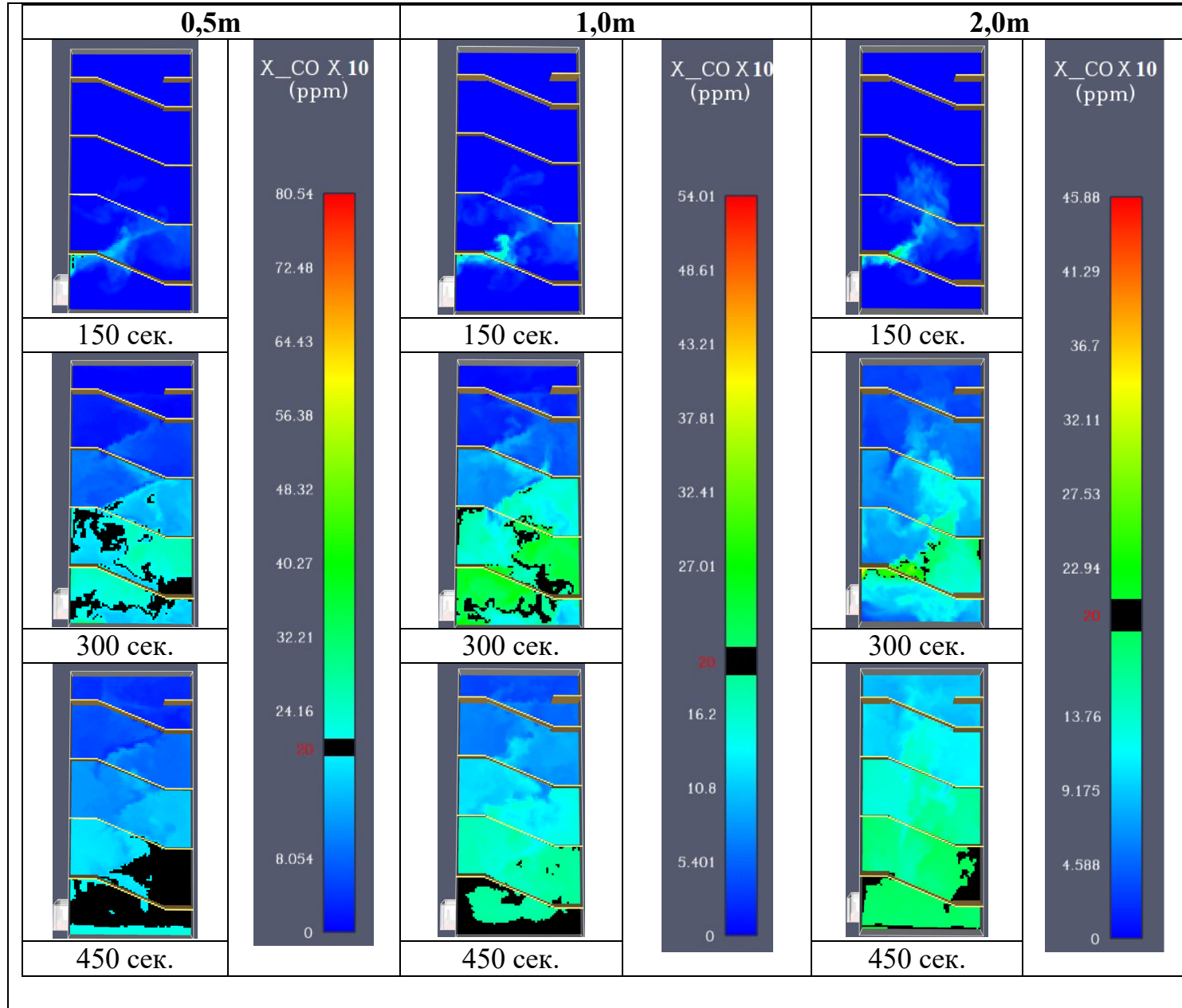


1 m



2 m

CO Concentration in the Stairwell



Application of Fire Dynamics Simulator in Tunnel Safety (Simulation Without Forced Ventilation)



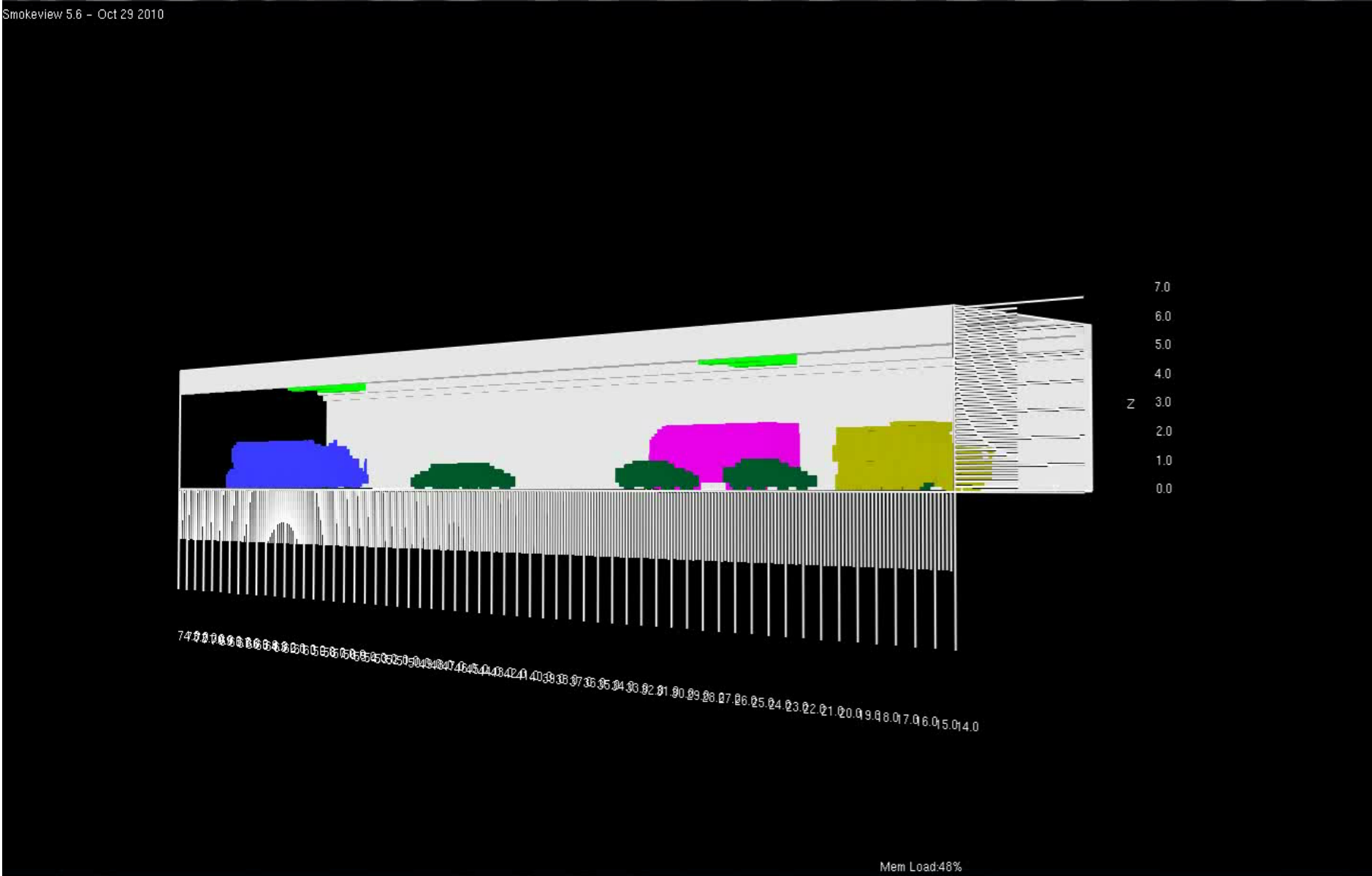
Application of Fire Dynamics Simulator in Tunnel Safety (Simulation With Forced Ventilation)



Tunnel with Vehicles – Without Forced Ventilation



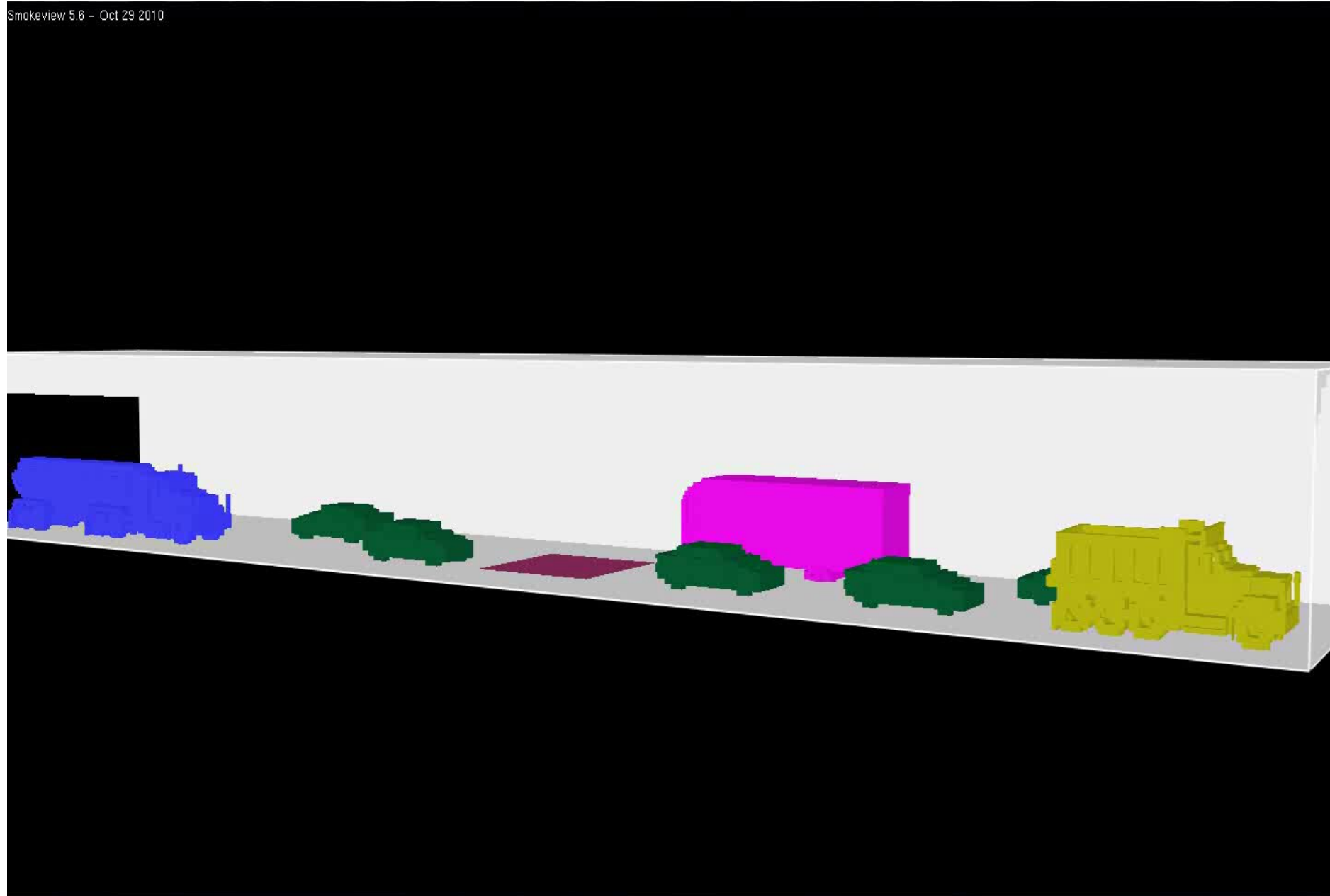
Tunnel with Vehicles and Forced Ventilation (Jet Fan 17.1 m³/s) – Backlayering



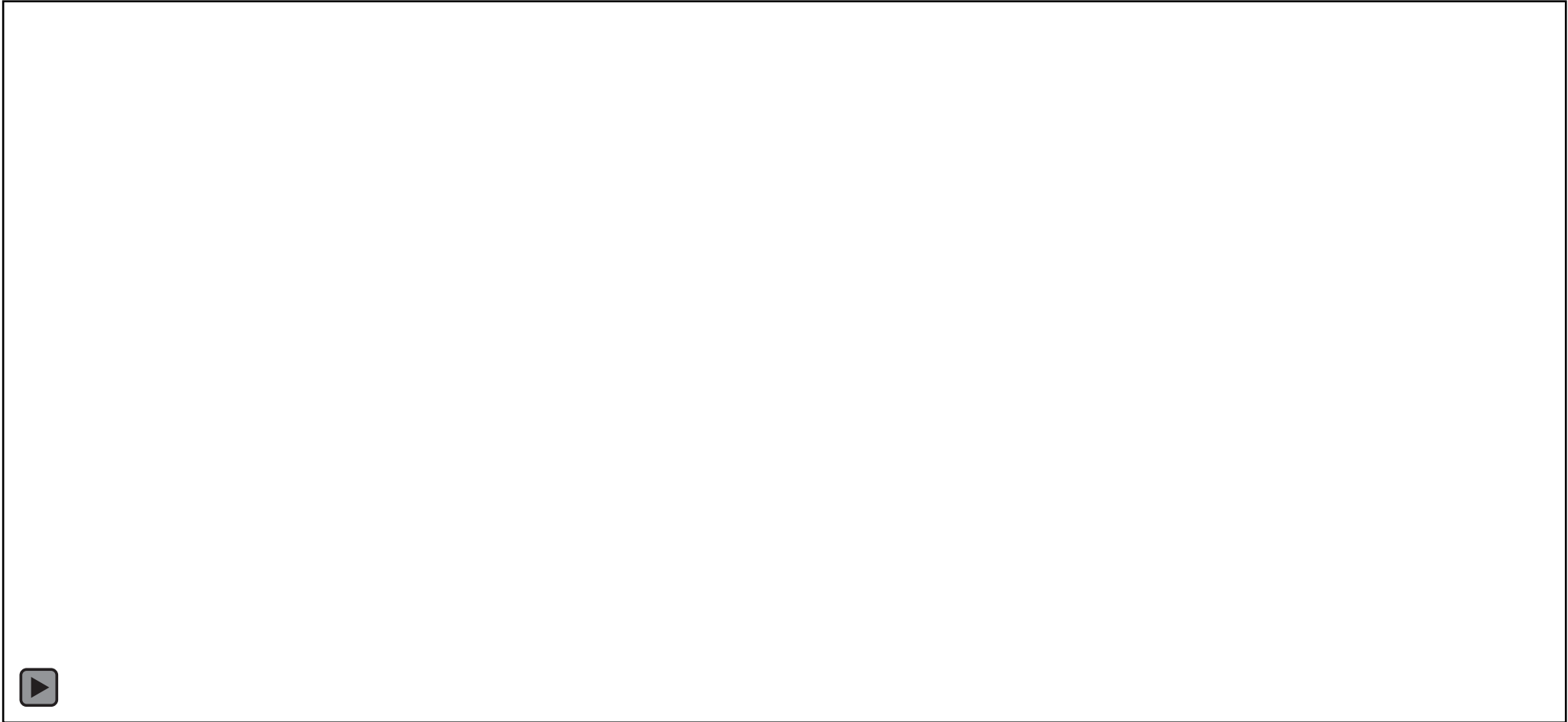
Tunnel with Vehicles and Increased Forced Ventilation (Jet Fan 34.2 m³/s)



Tunnel Equipped with a Sprinkler System



Application of Fire Dynamics Simulator in the Optimization of Smoke Extraction Systems in an Underground Garage

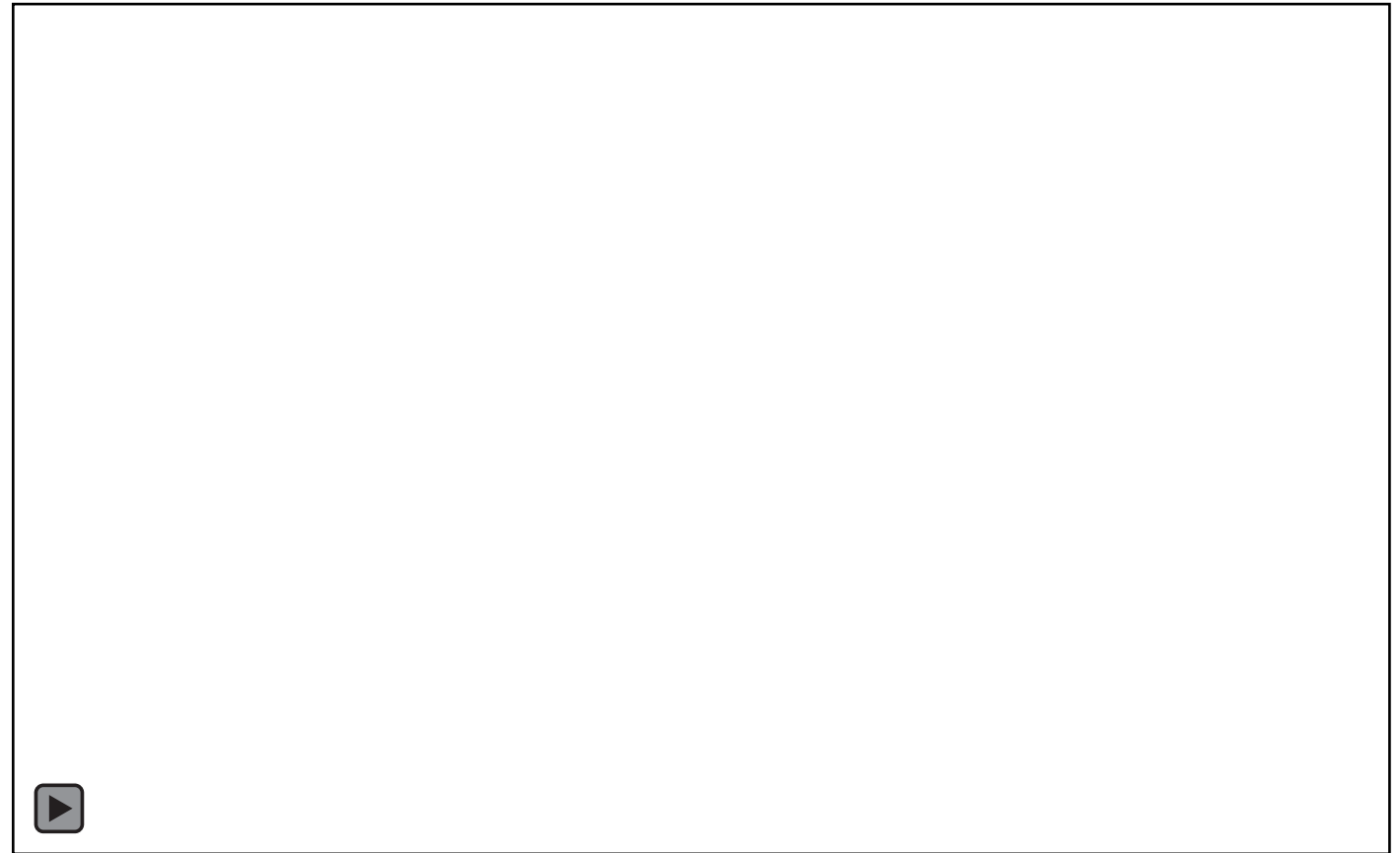


3D Model Layout of the Underground Garage

Application of Fire Dynamics Simulator in Optimizing Smoke Extraction Systems in an Underground Garage

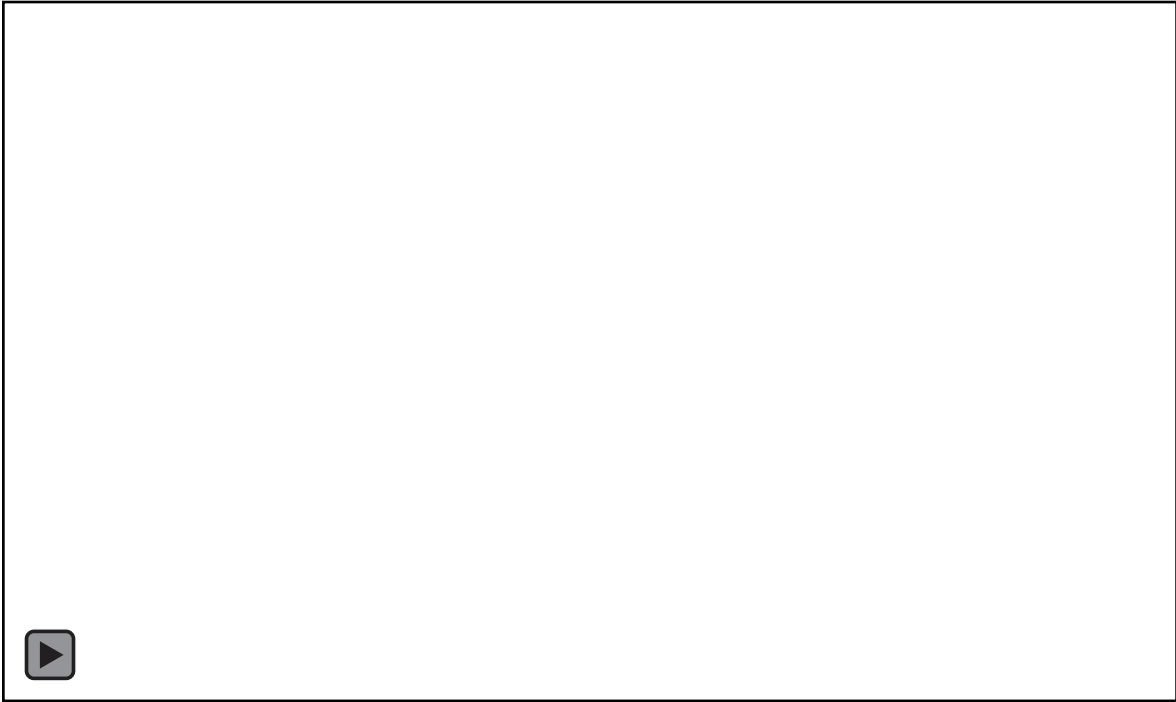
Scenario: Use of Lower-Power Jet Fans Arranged in a 2+3 Configuration

The upper rear fan is positioned in the far-right corner of the garage, so in this location it does not assist the central fan located immediately behind the fire source. Its airflow opposes the upward thermal flow of combustion products, thereby creating a circulation zone with counterflow directed toward the garage entrance.

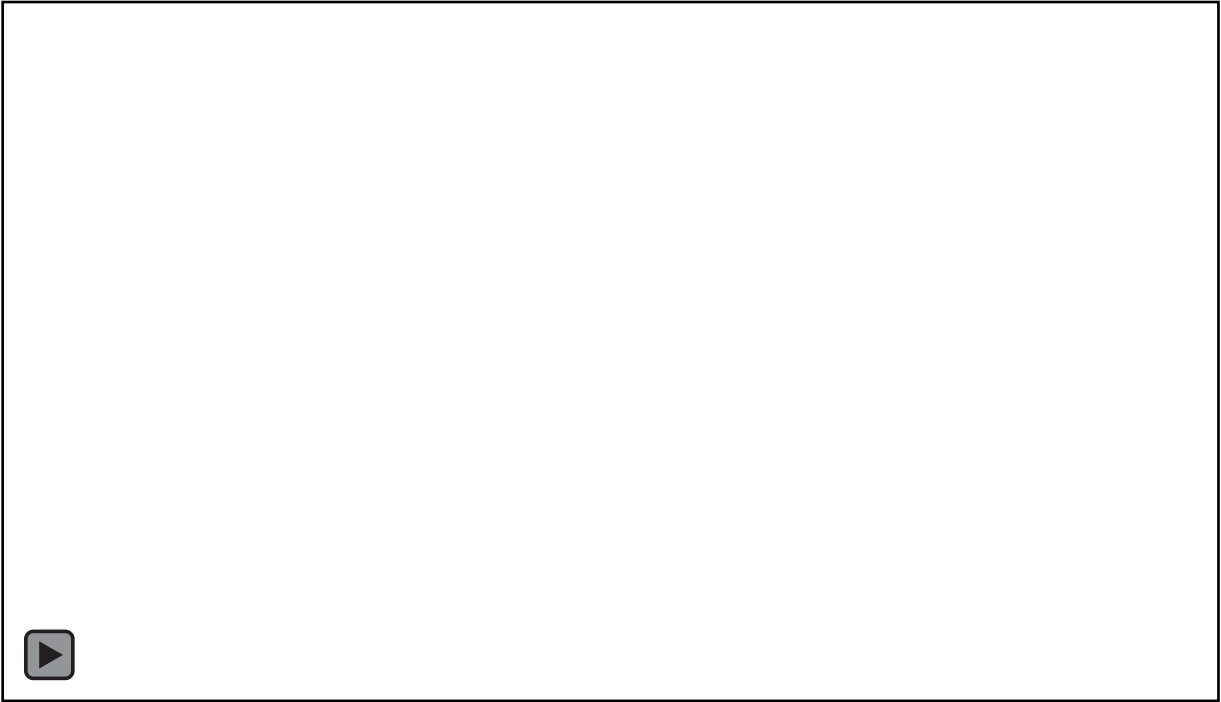


Airflow Velocity at Fan Height (2.5 m)

Application of Fire Dynamics Simulator in Optimizing Smoke Extraction Systems in an Underground Garage



Vertical Airflow Velocity



Airflow Velocity at Head Height

Application of Fire Dynamics Simulator in the Analysis of Railway Accident Consequences

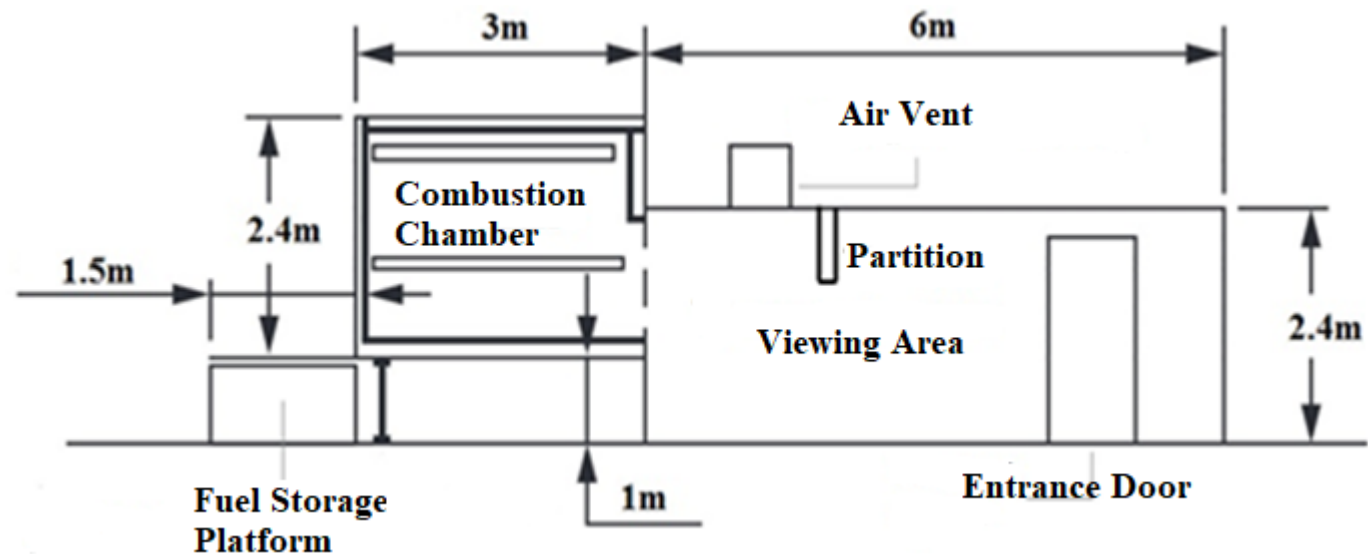


Application of Fire Dynamics Simulator in the Analysis of Railway Accident Consequences



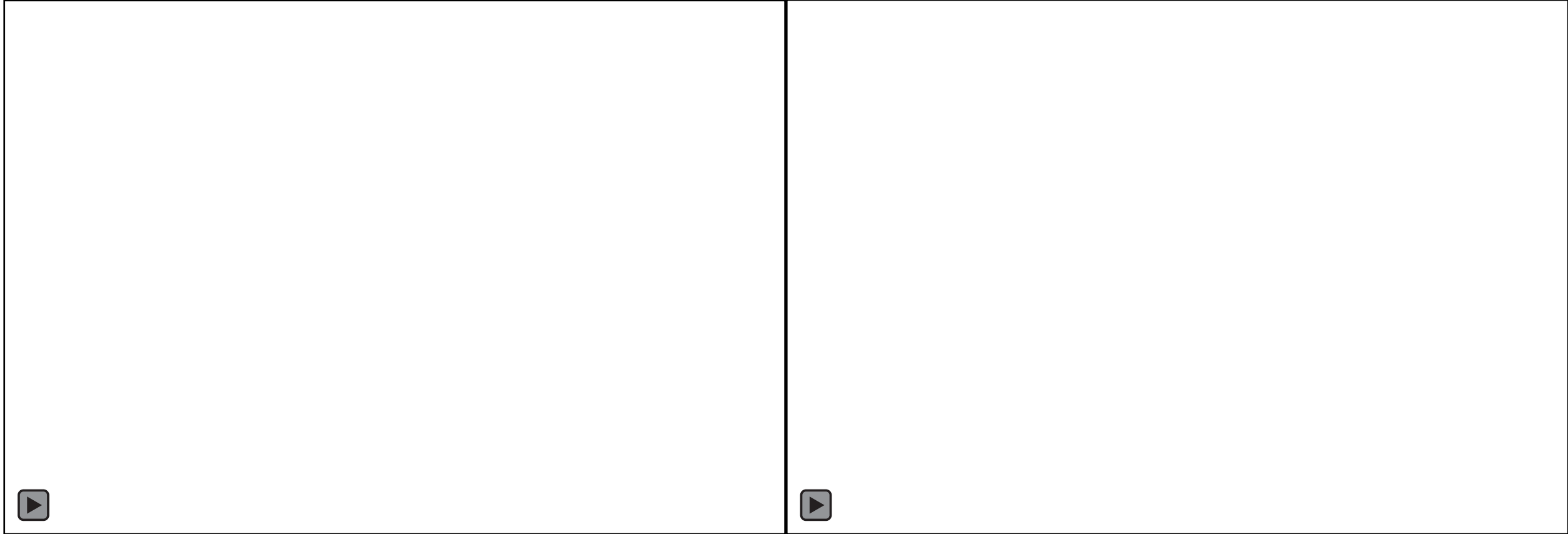
Application of Fire Dynamics Simulator in Firefighter Training – Flashover Container

Construction of the Flashover Container



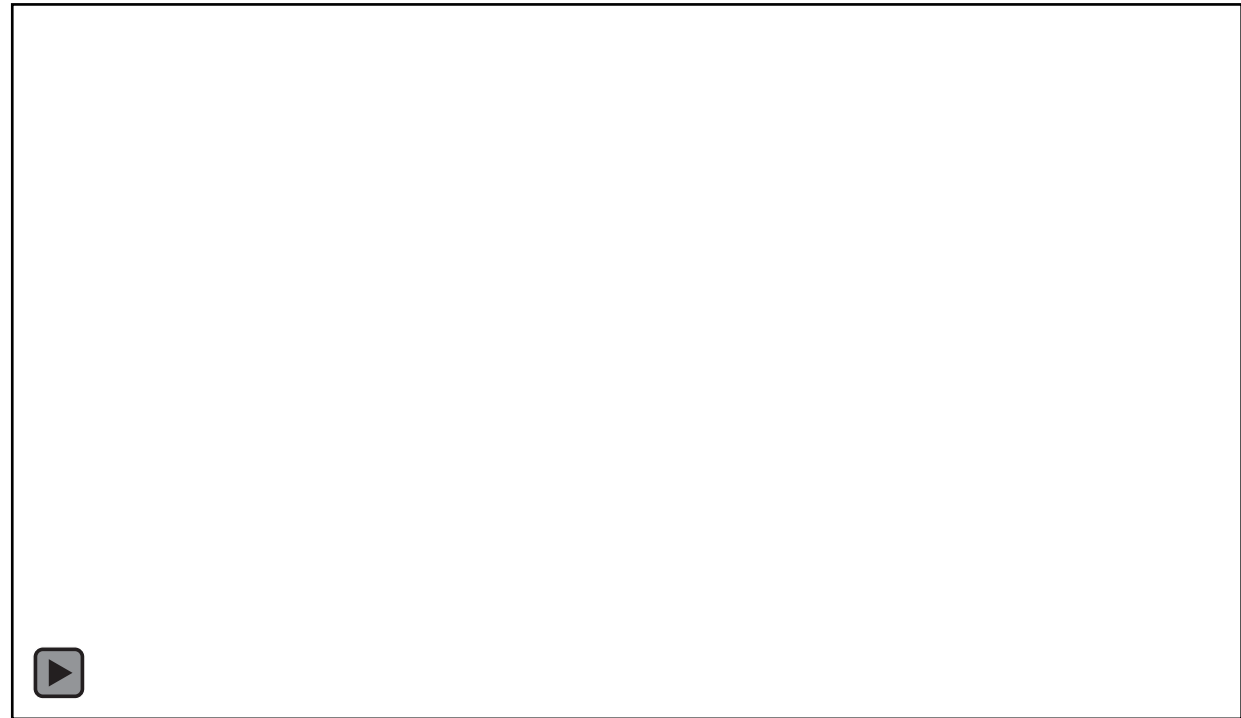
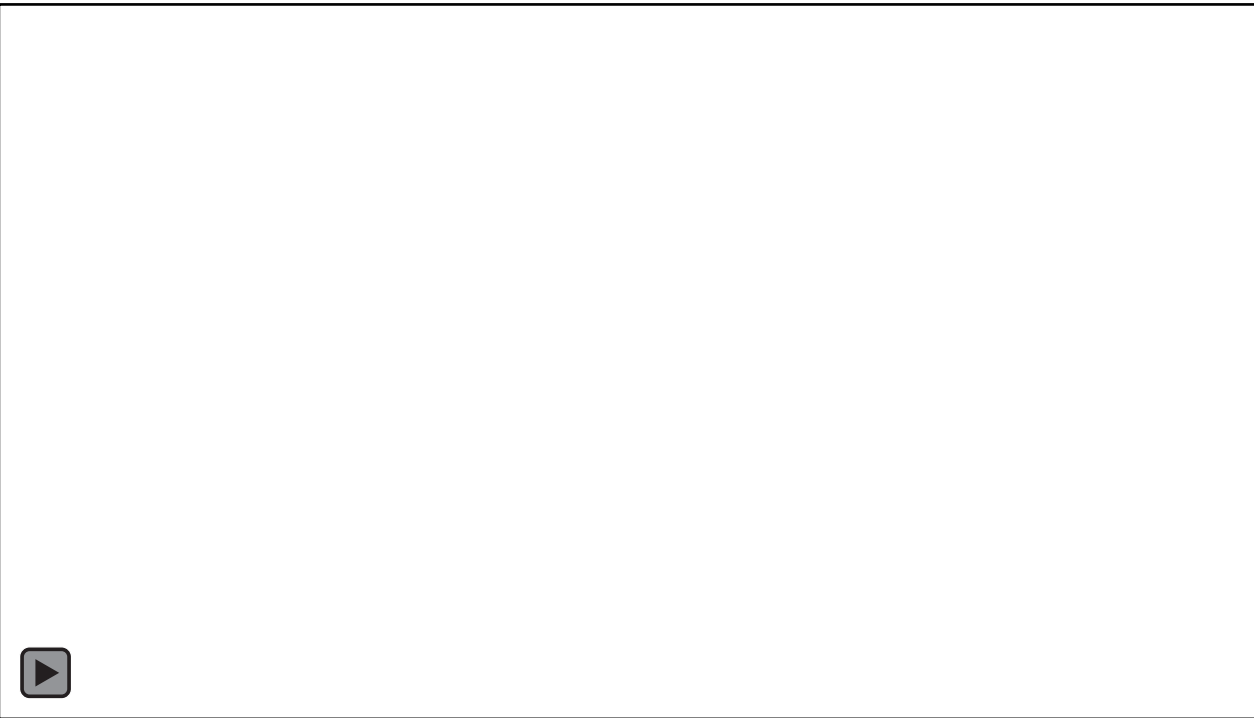
View of a flashover container constructed in accordance with the standard DIN 14 097 1/4

Setup of a numerical model for fire simulation



View of the 3D model of the flashover container and sensor arrangement

Scenario – roof opening and container doors open (favorable scenario)



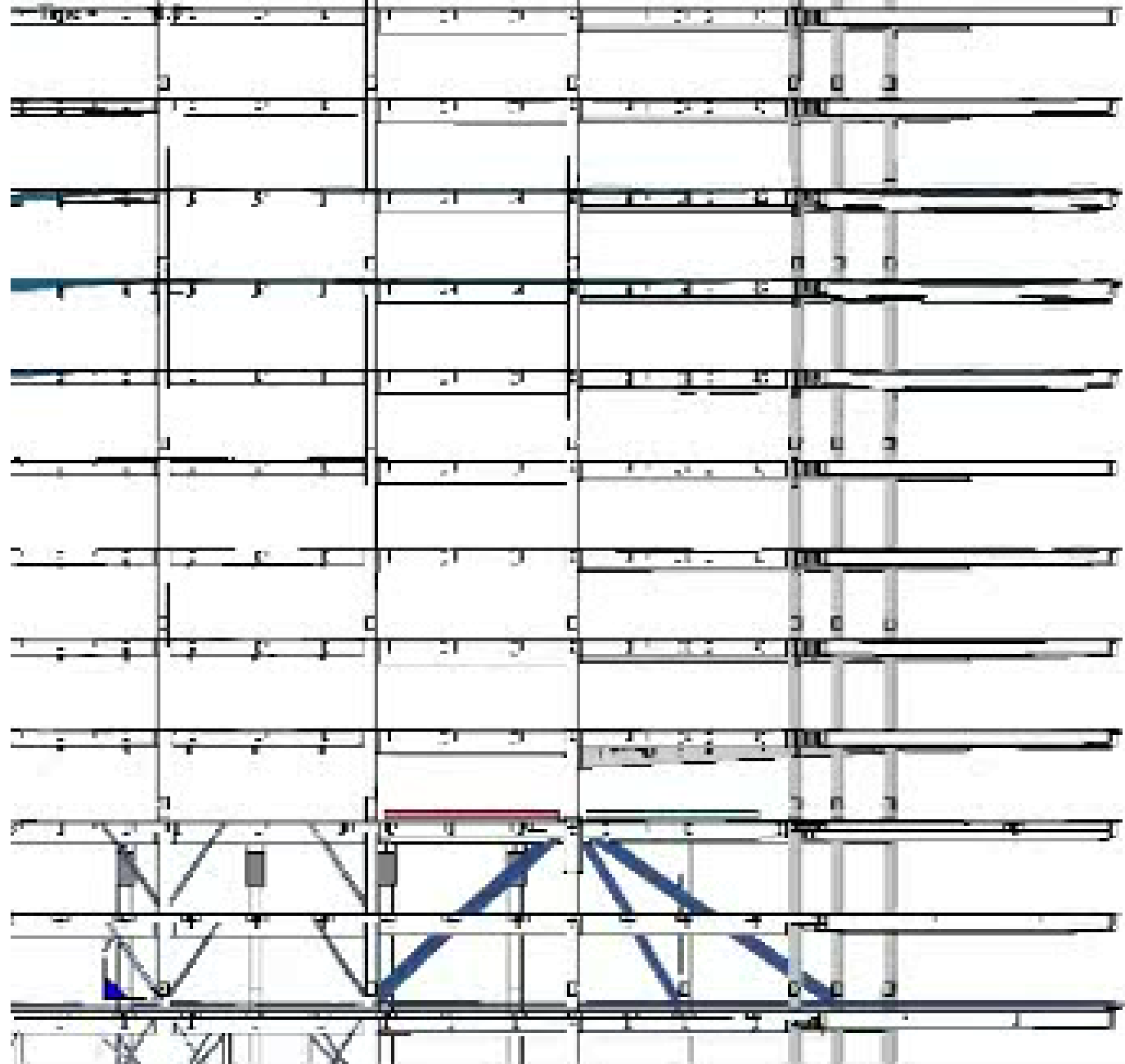
Visualization of fire growth and temperature distribution in a flashover container

The scenario is favorable, although the temperatures at the bottom of the container are lower due to excessive ventilation of the container and the slower attainment of the flashover point, which requires more time to conduct firefighter training. There is no danger to firefighters during the training execution.

Application of FDS for assessing structural fire resistance in the context of the World Trade Center Disaster



LS-DYNA Model of WTC-7



Software applications for fire modeling in wildland-urban interfaces (WUI)

- The rural-urban, i.e., uninhabited-to-inhabited interface (Wildland-Urban Interface, WUI) is a transitional zone where human presence, settlements, and property exist. From the perspective of fire hazard, these areas pose a significant risk and threat to the communities living within them, as fires involve interactions between the materials used in residential structures and various types of vegetative fuel, differing in type, size, spatial distribution, etc.
- For the prediction of fire ignition and spread in such environments, mathematical models have been developed, whose implementation depends on:
 - the collection and analysis of data on past fires in such areas, i.e., the formation of relevant databases containing information on the design and location of residential buildings;
 - the characteristics of building and vegetative fuel (fire load);
 - human activities present;
 - terrain topography;
 - meteorological conditions; etc.

Mathematical models for predicting fire occurrence and propagation in wildland-urban interface (WUI) areas

- **Models based on empirical and semi-empirical equations:**

- BEHAVE

- FARSITE

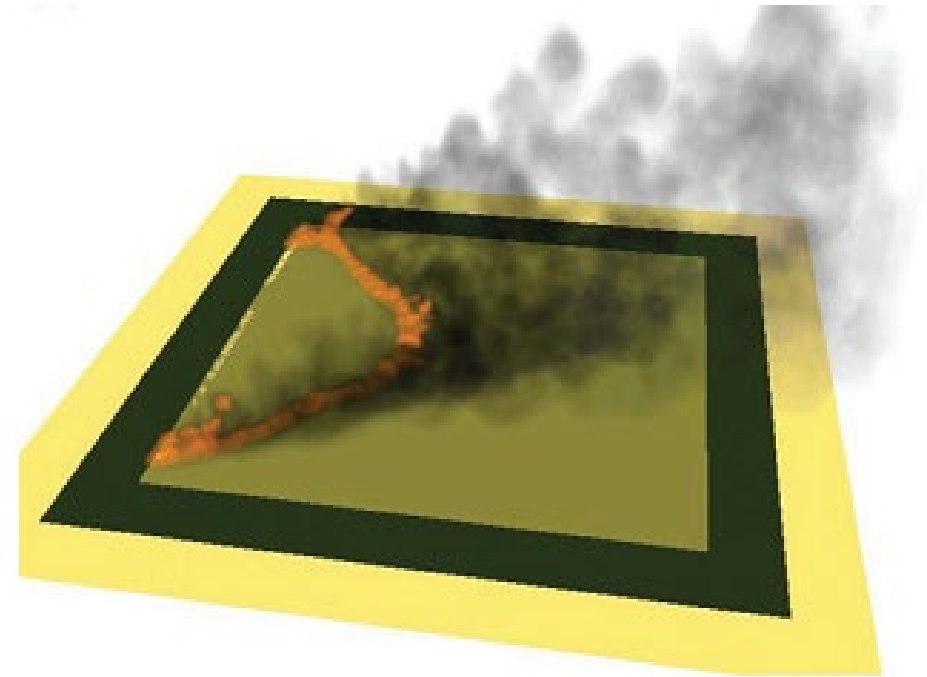
- **Models based on numerical fluid dynamics:**

- WFDS – Wildland-Urban Interface Fire Dynamics Simulator

WFDS - Wildland-Urban Interface Fire Dynamics Simulator

- The software package has been developed and is currently being refined at the BFRL (Building and Fire Research Laboratory) of the National Institute of Standards and Technology (NIST), USA, and represents an enhancement of the Fire Dynamics Simulator (FDS).
- It is based on numerical fluid dynamics used to solve three-dimensional (or two-dimensional) time-dependent equations of fluid motion, combustion, and heat transfer.
- The package also includes algorithms necessary for calculating fire spread in rural-urban environments containing various types of vegetation, such as trees, grass, shrubs, etc.
- For visualization of calculation results in the form of three-dimensional animations, the program SMOKEVIEW is used.
- It employs two methods for vegetation modeling: the **fuel element method** and the **fuel boundary method**. The fuel element method can be applied to model both surface and elevated vegetation. The fuel boundary method is applied only to model surface fuels and is designed to work only at coarser grid resolutions compared to the fuel element method.
- The software models heat and combustion product transfer rates, radiative and convective heat transfer, flame spread, and fire development. It calculates temperature, heat flux (radiative and convective), density, pressure, chemical composition of combustion products within individual computational grid cells, total heat release, and other relevant parameters.
- It is applicable in fire design and forensic reconstruction.
- It cannot be used for scenarios involving explosions or detonations.

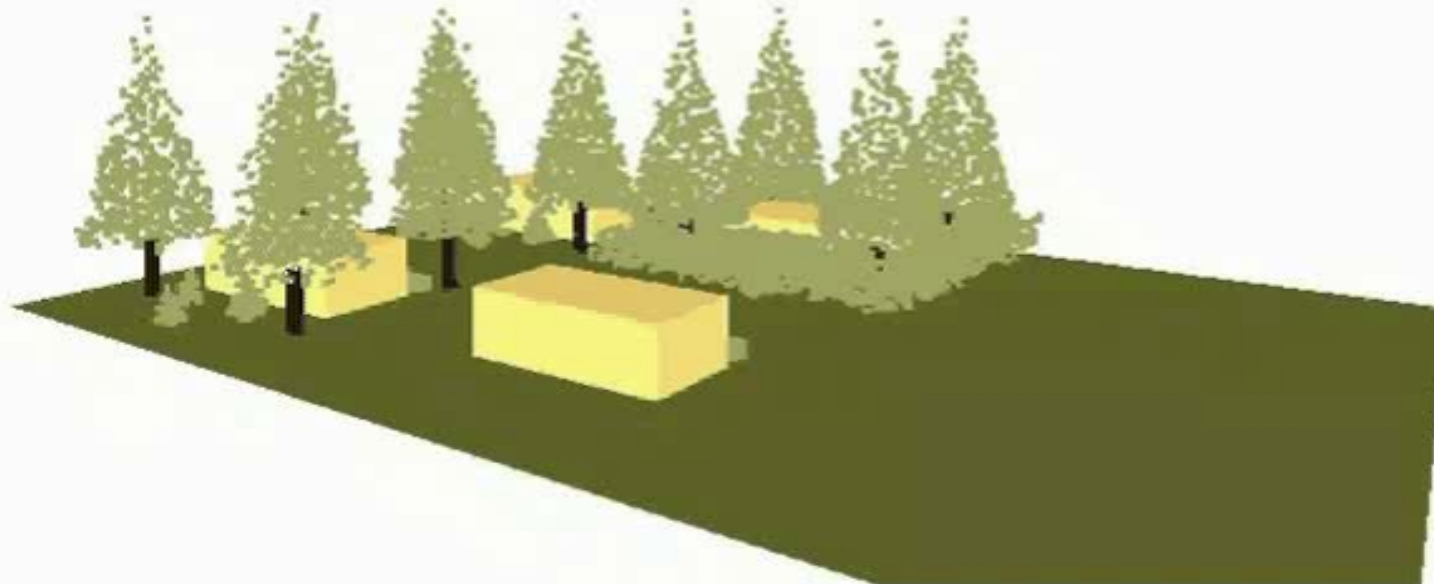
WFDS – surface fuel fire experiment



WFDS - Wildland FDS



Smokeview 4.0 Final Beta - May 14 2004

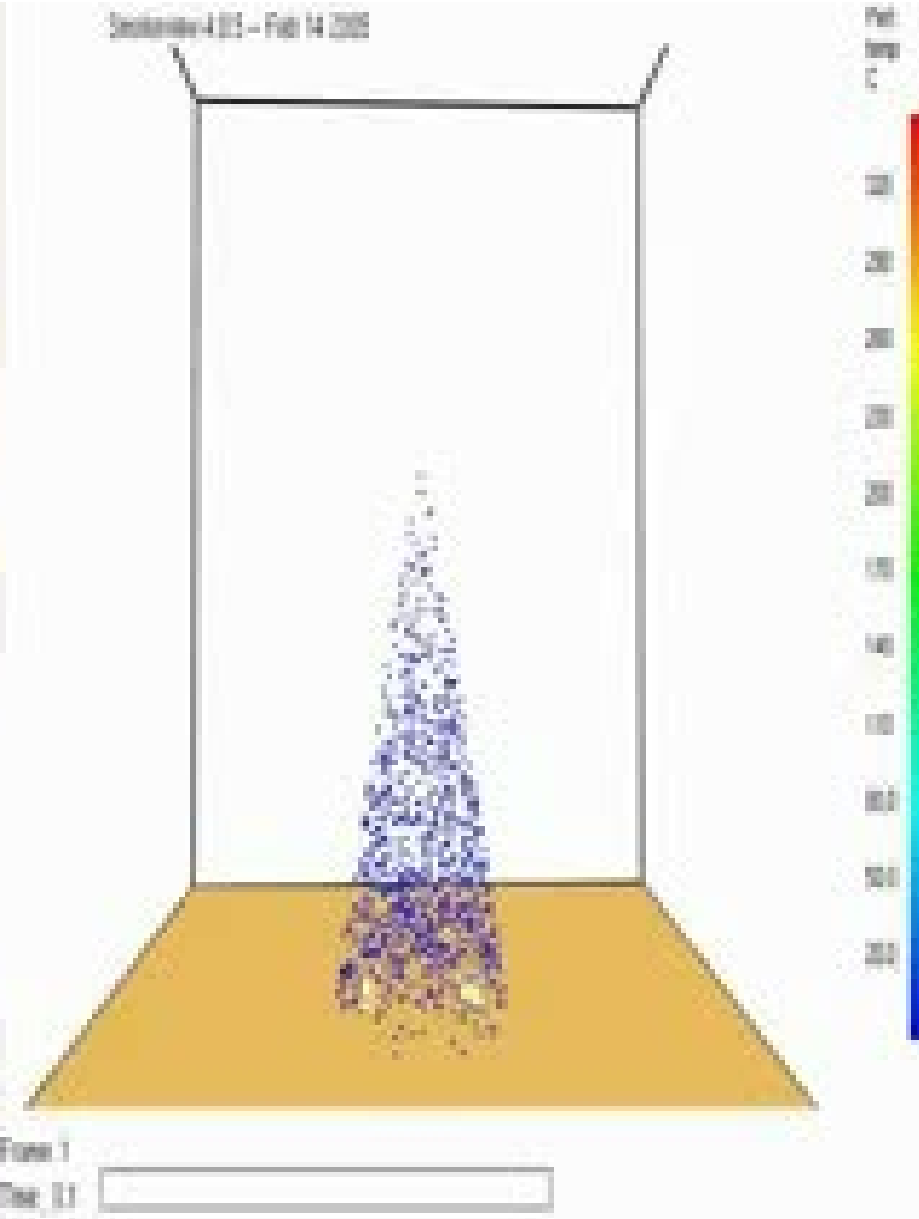


Frame: 0

Time: 0.0

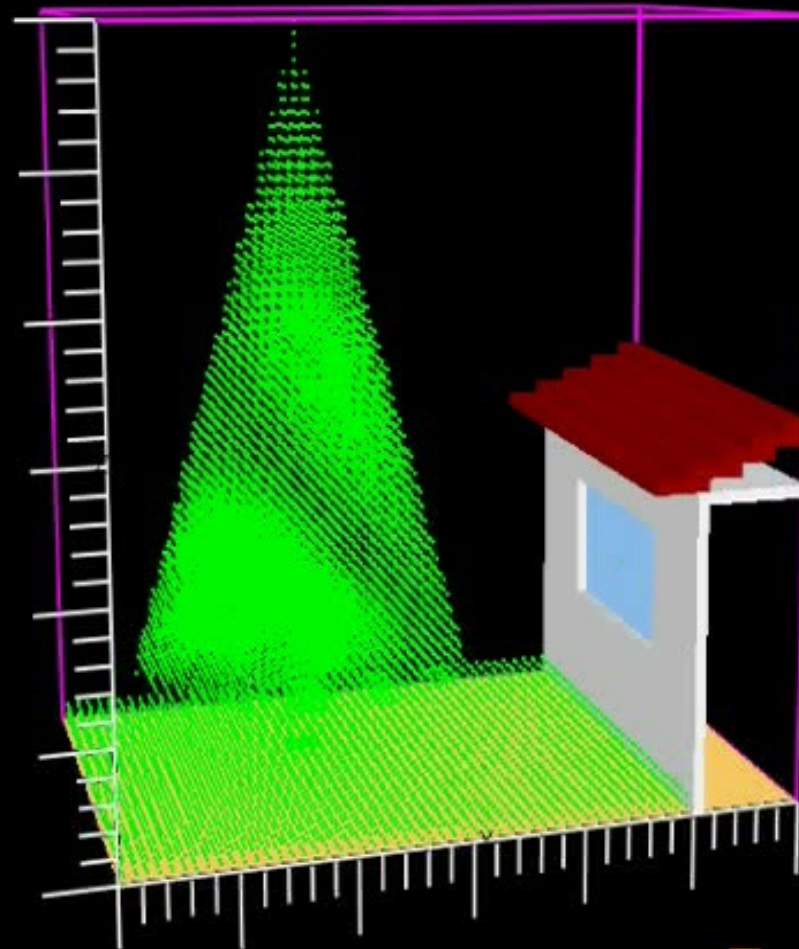



WFDS - Wildland FDS



WFDS - Wildland FDS

Smokeview 5.4.6 - Oct 22 2009



 >200 (kW/m3)



WFDS - Wildland FDS

Data on the thermal properties of the materials used

Residential building

Technical Properties of Materials						
Material	Thickness [m]	Density [kg/m ³]	Thermal Conductivity [W/mK]	Ignition Temperature [°C]	Heat of Evaporation [kJ/kg]	Burning Rate [kg/m ² s]
Gypsum board	0.013	1440	0.48	400	-	-
Spruce	0.028	450	-	360	500	-
Curtain (cotton)	-	40	-	280	1500	0.03

Vegetation fuel

Physical and Combustion Properties of Pine Components						
Material	Bulk Veg. Density [kg/m ³]	Veg. Density [kg/m ³]	Char Fraction	Max. Heat Release Rate [kg m ⁻³ s ⁻¹]	Moisture Content	Surface Area-to-Volume Ratio [m ⁻¹]
Pine needles (canopy)	2.2	520	0.25	0.4	1	4000
Trunk (pine)	520	520	0.25	0.4	1	3
Pine needles (litter/floor)	10	510	0.25	0.4	0.07	5710

Evacuation Simulation Software FDS+EVAC



Evacuation Simulation Software - Pathfinder



Pyrosim - FDS-based software tool



PATHFINDER and PYROSIM

