Project Description – Project Proposal

Prof. Dr.-Ing. Heinz Pitsch
Dr.-Ing. Dipl.-Wirt.-Ing. Joachim Beeckmann

Experimental and numerical investigation of wind-driven reacting firebrand dynamics in wildland-urban interface fires

---

Project Description

1 Starting Point

The recent wildland-urban interface (WUI) fires in Los Angeles (Fig. 1 left) have been a massive disaster, causing multiple fatalities and burning down large areas and countless structures. Among the various types of large outdoor fires, WUI fires, which are wildland fires that spread to urban areas, pose the greatest challenges to many countries worldwide [11–14]. Recent years showed that also different regions in Europe have increasingly been affected by WUI fires [12, 13, 15–17].

In Europe, Germany stands out as one of the most densely populated countries in the European Union with approximately one-third of its land covered by wildlands and forests. Historically, fire research in Germany has focused mainly on forest fires [19, 20]. However, recent WUI fires in Germany have posed significant challenges to infrastructure and fire services [21]. This issue is exacerbated by the fact that Germany and Europe as a whole lack adequate preparation to address the growing threat of WUI fires to its citizens [15, 16, 21]. Unlike typical wildland fires, whose fuel is the surrounding vegetation, and which are present in uninhabited areas [22], WUI fires burn vegetative and human-made fuels [22]. The plethora of fuels present in WUI fires, including house structures, is more complex than the vegetative fuels in wildland fires.

Figure 1: Actual firebrand shower in the recent California WUI fire (left) [Source: REUTERS/Ringo] and firebrand showers generated using a laboratory-scale firebrand generator (right) [18].

In WUI fires, ignition sources fall into the three main categories shown in Fig. 2, which often act in combination: direct flame contact, radiant heat exposure, and firebrand showers [18]. Although direct flame and radiant heat are significant, firebrand showers, which are burning embers carried by the wind (see Fig. 1), are especially dangerous, igniting structures and fuels far ahead of the main fire [18, 23]. Firebrands can spread fire across barriers such as roads or firebreaks, which would otherwise slow the flames [11]. This wind-driven fire spread mechanism by firebrand showers and its effect on shower deposition patterns is not yet clearly understood [24]. Investigating the underlying physics behind firebrand showers to provide predictive models is thus essential to WUI fire preparedness and community protection and can be extended to protecting forests facing wildland fires.

Figure 2: Exposure threats to buildings in WUI communities. Figure adapted from [18].

To this end, the interaction of the turbulent flow with the burning embers forming the firebrand shower will be investigated along with the resulting ground deposition patterns and their impact on heat transfer and surface ignition. We will refer to these aspects here with the term reactive firebrand dynamics. As part of the proposed effort, a laboratory-scale firebrand generator based on ISO 6021:2024 [25, 26] that was originally developed by the proposed Mercator Fellow, will be coupled to a wind tunnel to study the complex dynamics of firebrand showers. For the first time, heat transfer imparted to a surface by wind-driven firebrand showers will be determined. Gas-phase analysis will provide local gas composition, thereby facilitating a more profound understanding of reactive firebrand dynamics and firebrand shower ignition risk. These novel experiments will be complemented by numerical simulations to improve our understanding of the physical mechanisms governing firebrand showers. The findings will deliver information on ignition risks and provide new knowledge to ISO fire safety standards for outdoor fires and the built environment [27], enhancing WUI fire preparedness and mitigating the growing risks associated with these fires.

1.1 State of the art and preliminary work

1.1.1 State of the art

In the field of fire safety, the majority of engineering approaches have focused on understanding fires occurring inside buildings [28], rather than on WUI fires or outside fires approaching buildings. A WUI fire is not constrained to well-defined boundaries, and the interaction of topography, weather, and wind becomes critical. Firebrands are often considered the most dangerous ignition mechanism hardest to understand and predict [24]. They are responsible for most home losses in WUI fires [24, 25] due to their potential to travel very long distances under high winds [29] (see Fig. 1). Firebrands are similar to embers but with a slight distinction: ember refers to any small, hot, carbonaceous particle. If a single ember or a collection of particles gets airborne driven by wind and, as a result, can ignite additional fires, this is then called firebrands [29]. Burning vegetative and human-made fuels in WUI fires creates firebrands, and the processes may be categorized into generation [30–32], transport [33, 34], deposition [35–37], and ignition of other burnable substances [38–40].

The firebrand threat in WUI fires is difficult to study from a fundamental point of view [22, 41]. About a decade ago, Manzello et al. [25] developed a firebrand generator shown in Fig. 1, which recently became an ISO standard [26]. Little physical understanding exists of how firebrand showers deposit and transfer heat to burnable substances (fuels) in a controlled laboratory setting. Compared to other advanced areas of engineering, such as combustion science, no theory of the firebrand shower-induced ignition processes has been developed [24], although many reviews on firebrands identify this gap [24, 25, 41–43]. Part of the problem is that research efforts have avoided looking at the firebrand deposition and ignition problem in a direct manner. Instead, attempts have been made to simplify the problem. Figure 3 illustrates some of the attempts [44–47] representing a dynamic problem such as firebrand showers as a static process, while ignoring all relevant physics and chemistry of the issue. A recent study demonstrated, for the first time, that a static non-reacting heater intended to simulate a firebrand could not replicate the complex smoldering ignition behaviors of fuel beds exposed to firebrand showers [48]. The application of advanced diagnostics to better understand firebrands is a relatively recent development [49–51]. Prohanov et al. [49] employed thermal imaging to detect and track firebrands in laboratory-scale experiments. Thompson et al. [51] quantified firebrand production and transport by analyzing audio recordings from in-fire cameras employed in the field. Bouvet et al. [50] developed and improved [52] a field-deployable diagnostic tool for tracking firebrands and reconstructing their shapes. Despite these advances, previous studies have primarily focused on the transport of firebrands within the flow field, leaving the coupled complex deposition processes largely unexplored. The application of advanced diagnostics to simultaneously track firebrand showers, characterize their deposition patterns, and analyze the subsequent heat transfer to surfaces remains an open challenge. Another gap lies in gas-phase analysis near deposited firebrands. While earlier studies have utilized gas analyzers to measure global parameters such as bulk flow composition of species such as oxygen (O_2), carbon monoxide (CO), and carbon dioxide (CO_2), and total heat release rate downstream of fixed fuel specimens [32, 53], resolving the local gas phase composition near deposited firebrands was not addressed. Such localized analysis is required to improve the characterization of firebrand burnout processes and their direct relationship to the coinciding ignition events.

Regarding the simulation of firebrands, advancements in computational fluid dynamics facilitated extensive research on firebrand shower transport and combustion, focusing on revealing the interactions between firebrands and structural elements in WUI scenarios. Large eddy simulations (LES) gained interest due to their scale-resolving capabilities and adaptability to large length- and time-scale applications. Furthermore, several authors have modeled firebrand trajectories and landing distributions under non-reacting, but otherwise realistic turbulence conditions [54, 55]. LES can accurately capture turbulence influencing firebrand behavior and landing patterns under various flow conditions, essential for predicting wildfire spread dynamics [54].

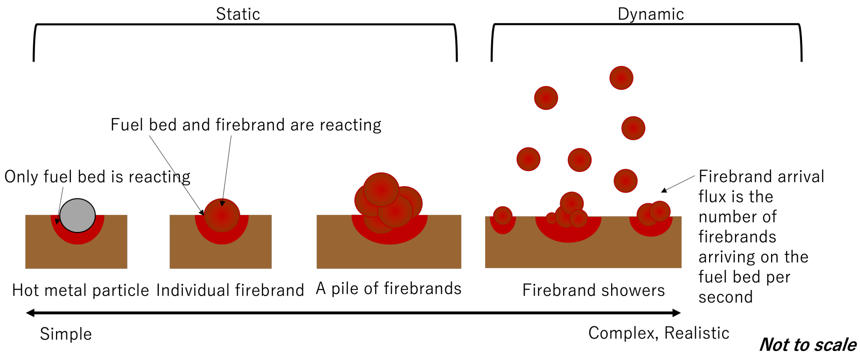

Figure 3: Summary of different approaches to understand firebrand deposition and ignition processes. Figure adapted from [41].

In modeling firebrand-laden flows, two main approaches, i.e., stochastic models and Lagrangian formulations, have been leveraged for simulating transport phenomena [55, 56]. Stochastic models offer an efficient way to model firebrand distribution across landscapes, where computational limitations prevent the tracking of individual firebrands. These models scale effectively in predicting general distribution patterns, have been validated against non-reacting wind-tunnel experiments [56], and have been applied in operational wildfire simulations [57]. In contrast, Lagrangian formulations focus on tracking individual firebrands [55]. This approach proved to be essential for studying short-range transport and deposition, where precise firebrand behavior is critical. Using the Fire Dynamics Simulator [55], researchers successfully replicated non-reacting firebrand deposition patterns observed in a controlled experimental setting with chemically inert particles. However, similarly rigorous validation studies for burning firebrands have not been performed [58].

Recent studies [59–61] have built on these models to investigate firebrand dispersion and deposition within WUI scenarios, which are crucial for assessing firebrand impact on structures. Research on firebrand deposition within WUI environments revealed the role of environmental variables such as wind speed and vegetation type in determining firebrand landing distributions [59]. Studies employing physics-based models provided input parameters for reduced-order wildfire simulations, such as firebrand generation rates based on environmental influences [59, 60]. Factors like wind speed and structural layout significantly affect firebrand accumulation between buildings, a vital consideration for mitigating fire spread in densely built WUI areas [61]. However, a gap remains in integrating firebrand burnout dynamics with transport and deposition models, particularly under high-turbulence conditions replicating WUI scenarios. Additionally, the impact of reacting firebrand burnout on dispersion, transport, landing patterns, and subsequent fire spread is unknown. Bridging these gaps requires a fundamental joint experimental/numerical approach covering the entire process from firebrand generation to firebrand deposition in WUI settings.

Knowledge gaps and potential impact:

1. Presently, no standard test methods consider wind-driven firebrand showers [29] because the technology to generate controlled firebrand showers in a laboratory setting has only recently been developed and standardized [26, 43]. In light of this advance, there remains significant lack of understanding the impact of the firebrand shower flux and the firebrand shower-turbulence interaction on deposition patterns and heat flux into fuel bed surface materials of building components and ornamental vegetation. Yet, it was shown that the unsteady nature of reactive firebrand dynamics impacts accumulation patterns and hence ignition behavior [24, 48]. Improved knowledge on these aspects can provide guidelines for realistic standard test configurations with unsteady firebrand shower mechanisms. This can lead to updated international test methods that allow for improved fire safety and better design of fire-safe materials.
2. The detailed processes of ignition from firebrand accumulation on fuel-bed surfaces is not yet understood preventing the development of detailed firebrand shower-induced surface-ignition models. This understanding will profit from a quantification of chemical species in the ignition region while a shower of firebrands accumulates on a fuel surface.
3. Validated predictive detailed or reduced-order models for reacting firebrand dynamics and firebrand-induced surface ignition are not available. Such models could drastically reduce the need for large-scale testing of new materials.

1.1.2 Preliminary work

Firebrand generator: To simulate wind-driven firebrand showers in the laboratory, a full-scale firebrand generator – the Dragon – was developed by the proposed Mercator fellow to allow for continuous and well-controlled firebrand showers to be generated and directed to real-scale building components. Extensive experimental campaigns were undertaken in a full-scale wind-tunnel facility to expose actual building elements to longer durations of firebrand exposures [25, 62]. For example, the Insurance Institute for Business and Home Safety incorporated the Dragon developed by Manzello and co-workers [25, 62] in their massive wind-tunnel facility to demonstrate the dangers of firebrand showers at the entire house scale.

While the full-scale continuous feed firebrand generator provided valuable insights into vulnerabilities of building components from firebrand showers, such experiments are costly to conduct, and it is difficult to perform many replicate experiments due to the scales involved. The application of advanced diagnostics is also a challenge at such large scales. It is hence immanent that a smaller-sized device is needed to develop international test methods and provide a better scientific understanding of the complex problem of firebrand shower ignition of fuel beds.

Therefore, a reduced-scale continuous-feed firebrand generator, which was called the baby Dragon, was developed by Suzuki and Manzello [43], forming the technical basis of the ISO Firebrand Generator [26].

Although scaled-down, the baby Dragon still produces real-scale firebrands providing realistic ember size distributions, ember densities, and ember load on surfaces. Experimental campaigns were undertaken using the baby Dragon in a 2 m $\times$ 2 m cross-section wind facility using smaller-sized fuel beds and mock-ups of building components. Firebrand deposition and accumulation processes were investigated [18, 63]. To provide a better understanding of the mechanisms involved in firebrand penetration into building vents, the scaled-down dragon was also used in an even smaller wind tunnel of 0.5 m $\times$ 0.5 m cross-section [62].

Optical and intrusive sensing techniques: The Institute for Combustion Technology (ITV) at RWTH Aachen University employs intrusive sensing techniques in various test facilities. On a systems level, advanced exhaust gas analysis has been employed using ABB emission cabinets for quantifying engine-out emissions regarding CO, CO_2, various hydrocarbons (HC), and nitrogen oxides (NO/NO_2) at response times in the range of seconds [64]. Further, highly dynamic measurements using high-speed continuous sampling tools like the Cambustion HFR500 and CLD500 have provided pollutant emissions data on HC and NO/NO_2 in the millisecond range [64]. CO and NO/NO_2 were also investigated in the context of condensing boilers using similar measurement devices and gas chromatography (GC) [**E1**]. On a fundamental level, ITV is proficient in conducting highly sophisticated speciation measurements using GC and time-of-flight mass-spectrometry to provide detailed information on the gas-phase chemistry of flames produced, e.g., in a counterflow burner [**E2**] or above a burning solid-fuel plate [**E3**].

Moreover, ITV's research capabilities encompass non-intrusive optical techniques, such as schlieren cinematography and particle image velocimetry (PIV). These methods have been employed to characterize fluid motion and particle trajectories on relevant spatial scales at high speeds. In previous studies, ITV has utilized these techniques, e.g., for measurements of flame propagation speeds [**E4**], for local velocities in turbulent slot-burner flames [65] and kinematic analysis of transient spherical hydrogen flames [66]. Building on this expertise in non-intrusive high-speed diagnostics, ITV will adapt methodologies for larger, irregular firebrands, facilitating accurate 3D trajectory mapping within a controlled wind tunnel environment.

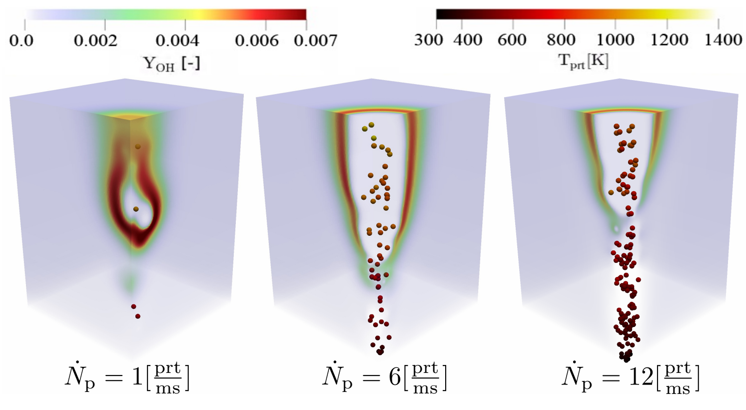

Figure 4: Direct numerical simulation of solid fuel flames in a co-flow jet configuration with different particle injection rates [**E5**].

Numerical simulation of firebrands: Firebrand dynamics will be simulated based on the existing numerical framework for modeling solid-fuel combustion, which has been developed at ITV within the in-house code CIAO [**E6**]. This solver can predict the reactive behavior of various solid fuels, such as different coal and biomass types, under a wide range of operating conditions relevant to practical applications, which has been demonstrated by validation against experimental measurements [**E5**, 67, **E7**, **E8**]. Due to the similarity between the fuel type of the firebrands generated during wildfires and solid biomass fuels [32, 68], the available numerical framework can also be used to describe transport and combustion processes of firebrands in a turbulent flow environment. Also, the extensive available numerical studies on the ignition and combustion characteristics of solid fuels can improve the understanding of firebrand dynamics. The flame topology of solid-fuel combustion under laminar conditions, as shown in Fig. 4, describes the impact of solid-fuel particle number density on flame characteristics. It has been found that particle-particle interactions can significantly impact the particle mass release and heating rate,

which affects the flame topology [E5]. Similar to embers in firebrand showers, solid biofuel particles can be quite large compared to the numerically resolved scales and they typically have non-isotropic shapes. In the context of point-particle formulations, a numerical treatment for finite cell-to-particle-size-ratio has been developed by Farazi et al. [E7], and the impact of shape and rotation on drag has been modeled by Fröhlich et al. [69]. Using analogies, the drag models can similarly be used for heat and mass transfer between particles and the surrounding atmosphere.
Due to the higher density of solid fuel particles compared to the surrounding fluid, non-zero Stokes number effects can be important and particles do not fully follow the flow. This can lead to particle clusters next to regions almost void of particles, which substantially affects ignition and combustion of particle clouds [E9]. These particle-turbulence-chemistry interactions for large Stokes number conditions are likely similarly important during firebrand combustion.

2 Objectives and work program

2.1 Anticipated total duration of the project

The anticipated total duration of the project is 72 months. The present proposal covers the first phase. It is expected that based on the results of the project, a follow-on project will be proposed covering possible topics as discussed at the end of this section.

2.2 Objectives

This project focuses on improving the understanding of the complex processes governing wind-driven firebrand showers, from their generation and transport in a turbulent flow to deposition and subsequent heat transfer into the surface material and ignition. By combining fundamental experiments and simulations, we aim to create comprehensive datasets for studying these scenarios under realistic, yet well-characterized conditions. A key priority is establishing a well-controlled environment featuring precise flow-field management and standardized firebrand generation to ensure experimental repeatability and to support advanced numerical simulations such as LES. We will analyze the reacting firebrands, quantify the reactive firebrand dynamics and their interactions with turbulence, and characterize deposition patterns alongside the heat transfer into a surface material. Ultimately, the project seeks to assess the differences between wind-driven firebrand showers and standard test procedures, where, for instance, firebrand material is placed at defined positions on an investigated fuel-bed surface before being ignited [29].
The main objectives of the proposed work are:

- **O1** Combining an optically- and probe-accessible wind tunnel with a firebrand generator to establish a well-controlled environment to study wind-driven firebrand showers, their interactions with turbulence, the evolution and burnout of firebrand showers, accumulation patterns on fuel-bed surfaces, heat transfer into the surface material, and ignition risks.
- **O2** Assess interactions of turbulence and reacting firebrand dynamics and its impact on firebrand dispersion using experiments and simulations. Test the applicability of state-of-the-art numerical approaches and identify areas of potential model improvements.
- **O3** Quantify differences in assessments of fire risk from wind-driven firebrand dynamics compared with standard static test procedures as, e.g., described in ISO/TR 24188 [29].

2.3 Work program including proposed research methods

2.3.1 Research methods

Concept: We will design a small-scale wind tunnel configuration that will be coupled with a firebrand generator to provide a well-controlled and -characterized environment for fundamental investigations of wind-driven firebrand showers considering three important aspects: firebrand generation, trajectories, and deposition with fuel ignition [60]. This facility produces firebrand showers with particle mass, particle projected areas, and particle flux similar to real WUI scenarios. The firebrand generator acts as a point-source for firebrands, and a realistic WUI firebrand shower can be seen as a superposition of multiple point-sources. The main limitation of the proposed setup is that it can only consider short-range firebrand transport. Figure 5 provides a schematic of the proposed setup.

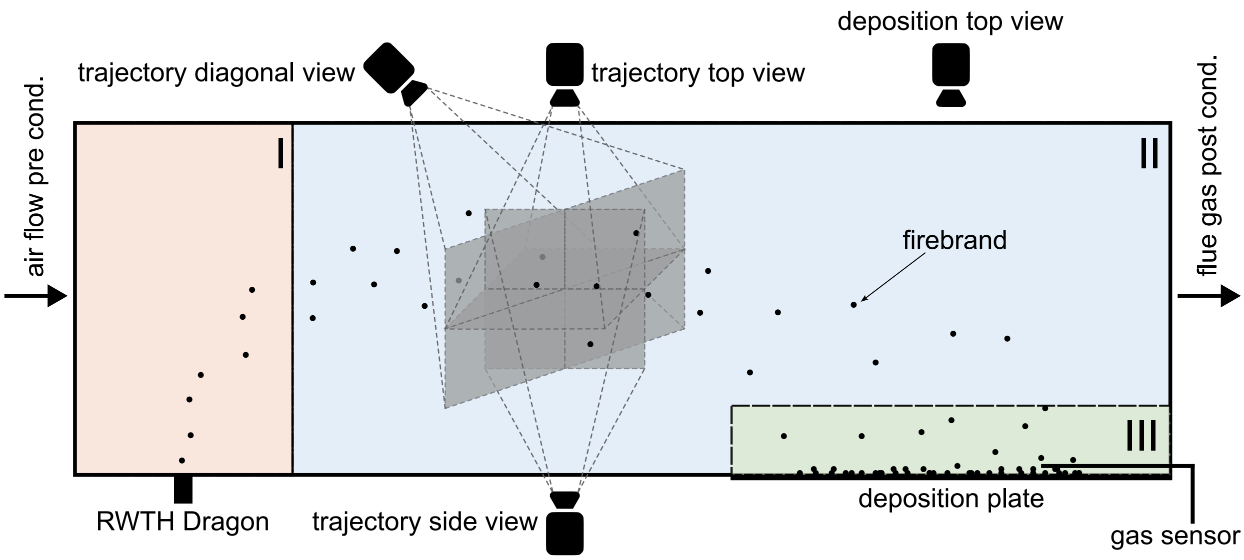

Figure 5: Wind tunnel concept with experimental setup highlighting the three firebrand aspects of interest: (I) generation, (II) trajectory, and (III) deposition. RWTH Dragon firebrand shower exit configuration without bend is shown.

The wind tunnel offers a controlled experimental environment with well-defined boundary conditions for simulations, ensuring experimental reproducibility and allowing for the study of firebrand behavior. Firebrands are generated (aspect I) using a small-scale dragon [26, 43]. This device produces burning particles with adjustable and well-defined conditions. For the study of particle trajectories and velocities (aspect II), three cameras track the movement of firebrands from the firebrand generator to the deposition plate. The optical setup allows for accurate trajectory tracking and facilitates shape determination, offering a broad perspective on firebrands, e.g., firebrand-turbulence interaction. In the deposition phase (aspect III), particles settle on a plate embedded either with thin-skin calorimeters (TSC) or with thermocouples (TC) enabling precise measurements of temporal and spatial heat flux into the plate. An auxiliary camera monitors the deposition process more closely. The analysis of gas samples collected at different points in the deposition zone further contributes valuable insights into the gas-phase composition throughout these experiments.

Wind tunnel: The wind tunnel consists of a $1\,\mathrm{m} \times 1\,\mathrm{m}$ rectangular cross-section and a length of $4.5\,\mathrm{m}$, excluding pre- and post-conditioning of the airflow. Pre-conditioning includes a fan to generate flow velocities up to $10\,\mathrm{m/s}$, a flow straightener, and an exchangeable fractal turbulence grid [70] producing turbulence at defined length scales. A monitoring system at the start of the test section will comprise thermocouples for the temperature and a hygrometer for the humidity. A constant temperature anemometer (DANTEC DYNAMICS) will be employed to characterize the velocity field in the inlet cross-section in terms of mean velocities and components of the Reynolds-stress tensor. These quantities are crucial as input for the simulations. Post-conditioning includes measures to prevent reacting particles from escaping the wind tunnel, e.g., a water curtain from an atomizing-spray unit. The base structure, the floor, and one lateral plate of the wind tunnel are made of stainless steel. The ceiling and the other lateral plate are made of glass to allow for optical access. The lateral steel plate can optionally be replaced fully or partially by a second glass plate. One side includes a swivel unit for easy access to the wind tunnel interior. The floor contains a recess a the end of the wind tunnel to mount the deposition plate.

Firebrand generator: A laboratory-scale version of the firebrand generator, termed RWTH Dragon in the following, will generate a continuous flow of reacting particles, i.e., a firebrand shower. The design of the RWTH Dragon will be based on the ISO Firebrand Generator [26, 43] depicted in Fig. 6. It consists of the main body and a continuous feeding component. A conveyor is used to feed wood pieces continuously into the device. The wood pieces drop onto a mesh and are ignited with a propane burner. The main tube is fed with an adjustable carrier-air flow from the bottom and the particles are carried upward once they have burned off to a critical mass. The firebrand shower exit will be tested with the bend (bend configuration, see Fig. 6) and without the bend (straight configuration), the latter providing better-defined boundary conditions for simulations. In contrast to previous investigations, where the firebrands were carried mostly by the exit jet of the dragon, for the bend configuration, the firebrand shower exit will be adjusted in diameter to approximately match the velocity from the wind tunnel. The vertical position of the RWTH Dragon exit in combination with the inlet momentum allows to modify the firebrand flight time, i.e., residence time, while keeping the distance of firebrand deposition unchanged. The RWTH Dragon produces firebrands with well-defined particle flux, ember load on target fuel-bed surface, and properties including material type, size, mass, and shape representative of those in realistic scenarios, where, for instance, typical ember size and mass are 1 cm and 0.05 g (see, e.g., Refs. [18, 48] for details). European spruce will be used as firebrand material. The feed material will be characterized by determining particle weight and by performing proximate analysis (quantifies moisture, fixed carbon, volatile matter, and ash content) and ultimate analysis (quantifies elemental composition). The ejected firebrands will be characterized by collecting these at the dragon exit in water or liquid-nitrogen pans for shock-quenching, and subsequent drying (easier with nitrogen), weighing, and performing proximate and ultimate analyses. This information will be used in the simulations.

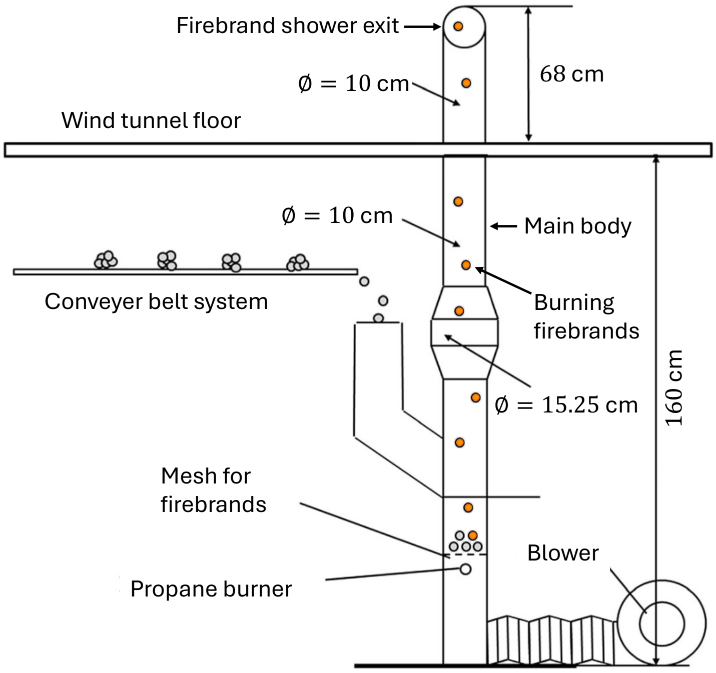

Figure 6: The RWTH Dragon based on the ISO Firebrand Generator [26] shown in bend configuration. Adapted from [18].

Optical diagnostics: The diagnostics to track firebrand shower trajectories and velocities will be based on those available in the literature [49–51]. A three-camera setup tracks the particle trajectories (see Fig. 5). Consumer-grade cameras with adequate spatial and temporal resolution, e.g., Sony DSC RX10 IV, will be employed. Two cameras are dedicated to track the vertical (side view) and horizontal (top view) firebrand trajectories. The third camera (diagonal view) increases the volumetric resolution [50]. We will reconstruct the trajectories in every dimension mainly based on the two planar trajectories. Approximate particle velocities consistent with the spatial and temporal resolution will be evaluated using commercial or adapted in-house PIV algorithms [65]. Simultaneous single-shot images from all three cameras supported by a dedicated light source, e.g., a flash lamp, facilitate determining the reacting particle shapes. We will install an additional consumer-grade camera above the deposition plate to track firebrand deposition over time (see Fig. 5). Here, exchanging the ordinary camera with an already available infrared camera may provide additional information on the firebrand deposition process regarding radiation and spatial distribution.

Deposition plate: We will control the particle trajectories such that a major part lands on the installed deposition plate. Three plate configurations will be used. The TSC-plate comprises TSCs embedded in a plate of an insulating substrate such as, e.g., in Refs. [44, 47], to record the local surface temperature and heat flux. The TC-plate consists of a stainless steel plate insulated to the wind tunnel floor, which is equipped with thermocouples on both sides of and inside the plate providing a spatially averaged temperature evolution, from which a spatially averaged heat flux may be derived. The fuel-bed plate will hold actual fuel beds to determine time of smoldering ignition on a given material. Here, European spruce and oriented strand board (OSB) will be used representing a vegetative and a human-made fuel. The plate size will be determined during the initial tests. The first two configurations provide similar information at different spatial resolutions, which, therefore, will also provide a cross-check. The number of sensors and the layout depend on spatial resolution requirements. Similar to finding the appropriate size of the deposition plate, we will determine the number and layout of the TSCs and thermocouples based on initial tests. Post-processing the data will provide temperature and heat-flux maps. These maps along with firebrand accumulation maps from the optical measurements will be correlated with smoldering ignition characteristics measured for both surface materials.

Gas phase composition: A gas analyzer (testo 350 - Analysis Box for exhaust gas analysis systems) with a wide measurement range draws samples at different locations above the deposition plate to provide the local gas-phase composition. The sampling device's design minimizes particle collection protecting the analyzer and preventing sample falsification. Sampling will be performed either from downstream of the plate or from the side. The testo 350 holds up to six sensors, facilitating the analysis of six species simultaneously, and allows for on-site sensor exchange and, thus, easy adaption to specific and varying measurement targets. We will pre-select four sensors for important devolatilization gases and gas-phase reactants, stable intermediates, and products: O_2, CO, CO_2, and methane. The additional sensors are two of the following options: NO, NO_2, propane, and butane. These measurements will support modeling of the heat release from deposited firebrands and could serve as early and more accurate indication for smoldering ignition compared with the commonly applied visual determination (e.g., Ref. [43]).

Firebrand simulation framework: The simulation of reactive firebrand dynamics will be conducted using LES to capture key flow dynamics and combustion processes. Firebrand dynamics involve complex interactions between the gas phase and the burning particles, including mass, momentum, and energy transfer. Resolving particle phenomena across all scales in a wind-tunnel setup is computationally prohibitive. Therefore, the interaction between gas and particles will be modeled using a fully coupled Euler-Lagrange framework with a point-particle approximation, where gas-phase equations are solved in an Eulerian frame, and particles are tracked in a Lagrangian frame to capture mass, momentum, and energy exchange. The LES framework is based on the in-house code CIAO, a high-order finite-difference solver for reacting Navier-Stokes equations in the low-Mach limit [71]. The code has been validated in solid-fuel combustion studies [**E5**, 67, **E7**], demonstrating its applicability for reactive firebrand dynamics due to the similarities with solid-fuel combustion. Due to the relatively large size of the firebrand particles, a filter kernel as suggested by Farazi et al. [**E7**] is used. The gas-phase chemistry will be modeled using a multi-stream flamelet progress variable (FPV) approach [72] with precomputed flamelet tables from counterflow-diffusion flames assuming unity Lewis numbers. Gas-phase kinetics will use the mechanism by Cai et al. [**E10**], which has been widely used in solid-fuel combustion studies [**E5**, **E9**, 72]. Particle-phase combustion processes, including devolatilization, char oxidation, and ash formation, will be modeled using reduced-order kinetics [**E5**, 72, 73]. These models have been calibrated against detailed mechanisms to ensure accurate predictions. The LES framework will be used in combination with experimental data to assess the applicability of the Lagrangian models for the complex interaction of burning particles, turbulence, buoyancy, radiation, and particle shape effects. It will also serve to analyze the effects of particle size, material composition, and flow conditions on reactive firebrand dynamics under wind-tunnel conditions.

2.3.2 Work program

This research aims to advance the understanding of firebrand combustion, transport, and deposition in WUI scenarios addressing critical gaps in modeling and standardization. It is subdivided into **three work packages (WP)**. The study begins with designing, commissioning, and characterizing a modular wind tunnel setup (**WP1**) integrating i) the RWTH Dragon for firebrand generation, and ii) advanced measurement systems to analyze trajectories, deposition patterns, and heat transfer. Building on this, **WP2** will explore firebrand behavior in a controlled environment studying the influence of flow-field conditions (e.g., wind speed, turbulence) and particle properties (e.g., size and mass flux) on deposition patterns, heat transfer into a fuel bed, and ignition characteristics. In **WP3**, the LES framework will be validated for non-reacting and reacting cases using the experimental data sets. The simulation results will identify modeling needs, support the analysis, and complement experimental findings.

WP1: Design, commissioning, and initial characterization of the wind tunnel setup
In this work package, we will design and commission the wind tunnel setup. We will also conduct tests for characterizing and validating the setup.

Task 1.1 - Installation and test of the wind tunnel infrastructure As the first step, we will set up the flow pre-conditioning unit, which integrates the fan, flow straightener, a reference fractal turbulence grid, and the flow monitoring system. We do not control or alter the flow temperature and humidity in this project phase. In the second step, the test section is mounted. In the third step, the post-conditioning unit, including a water curtain from an atomizing-spray unit, is installed. In the last step, the entire wind tunnel is characterized for different flow conditions. This involves constant temperature anemometry-measurements of the gas velocities for the test-section inlet cross-sections and at various positions throughout the wind tunnel to quantify the interactions of the grid-generated turbulence with the developing boundary layer in the channel.

Task 1.2 - Installation of the RWTH Dragon For the firebrand generation, we will install the RWTH Dragon just downstream of the test section inlet. The installation is concluded by conducting initial tests with the entire setup. Inert firebrand ejection is followed by flaming or smoldering firebrands. Initial tests aim to characterize the firebrand ejection behavior for the two different exit configurations and to evaluate the protruding length of the RWTH Dragon outlet from the wind tunnel floor. Potentially, obstacles downstream of the observation area (see, e.g., Ref. [43]) could be included in this step to achieve more realistic deposition patterns. In this task, also the firebrand characteristics will be determined from proximate and ultimate analysis.

Task 1.3 - Setup of optical equipment for tracking firebrand trajectories We will set up the optical equipment to analyze firebrand trajectories. This includes mounting and aligning the cameras to cover the volume of interest. Initial tests involve tracking single non-burning (as discussed below in Task 2.3) and burning firebrands. This will result in a preliminary quantitative data set for non-burning particles at a reference condition, which will be used in WP 3 for early tests of the simulation framework.

Task 1.4 - Setup of firebrand deposition monitoring equipment The TSC- and the TC-deposition plates have redundant information for homogeneous heat load, which will be cross-validated by applying heat from an electric radiant heater. The deposition plates will also be tested by manually placing ignited firebrands. This will provide reference data sets used later in the project for comparing with wind-driven firebrand data. Also, the appropriate sampling device for the gas-phase species measurements will be installed in this task. Initial tests will support selecting the suitable sensor configuration.

WP1 Milestones 1. Set up and test of wind tunnel infrastructure. 2. Installation and tests of the RWTH Dragon. 3. Set up of the measurement equipment. 4. Reference data sets for non-reacting wind-driven particles and reacting deposited particles in quiescent environment.

WP2: Characterizing the impact of flow-field and firebrand properties on firebrand deposition patterns, heat transfer, and fuel-bed ignition

The primary objective of this work package is to characterize how flow-field conditions and firebrand properties influence deposition patterns, heat transfer into the bed material, and ultimately the time to smoldering ignition. The data sets will include five different observables. First, we will track firebrand trajectories using the three-camera setup. Statistical evaluation methods will provide important firebrand metrics such as particle number density, fuel mass flux, particle velocities, and joint distributions of shape and size. This analysis will provide insights into the different firebrand properties generated by the RWTH Dragon and how these interact with varying flow conditions. Second, deposition patterns will be observed. We will employ statistical techniques to examine the patterns of deposited firebrands and link these to the modified fuel and flow parameters. Visual monitoring of the deposition process will support determining firebrand distribution. Third, processing the deposition-plate data will result in maps of temperature and spatial heat flux into the deposition plate. Fourth, gas sampling close to the deposited firebrands will provide further information on firebrand burnout after deposition on one of the inert plates. The testo 350 measures the gas composition continuously, facilitating temporally resolved recording of deposited firebrand burnout and the impact of newly deposited particles on the burnout process. Fifth, experiments carried out using the fuel-bed plates will provide time to smoldering ignition. Here, the gas sampling will provide an ignition criterion. In case the times to smoldering ignition are too long, fuel-bed materials can be pre-heated [38].

Pertinent parameters impacting the observed quantities include firebrand particle size and ejected mass flow rate, wind speed, the integral length-scale of the turbulence, and the fuel-bed material. Studying these parameters will be the focus of the proposed work. Independent variations of further parameters, such as other turbulence parameters or firebrand and fuel-bed shapes and materials will not be considered here.

Task 2.1 - Reference measurements In this task, we will perform measurements with reference values for firebrand size ($\leq 5\,\mathrm{mm}$), ejection frequency given by the particle feeding rate into the dragon, wind speed ($\leq 5\,\mathrm{m/s}$), and an intermediate integral length scale set by the fractal turbulence mesh. The reference values will be determined in initial tests. The fuel-bed ignition tests for the reference case will be performed for the European spruce.

Task 2.2 - Sensitivity analysis In a second step, firebrand particle size and ejected mass flow rate, wind speed, and the integral length-scale of the turbulence will be varied individually. For each parameter, measurements will be performed for two additional values, typically one larger and one smaller than the reference value. Also the sensitivity of time to smoldering ignition with respect to the fuel-bed material will be determined by using an OSB plate.

Task 2.3 - Measurements for non-reacting firebrand particles For the reference condition from Task 2.1 and for one additional individual variation in particle size, wind speed, and integral length scale, non-reacting experiments will be performed. The variations will be taken from those used in Task 2.2. For these measurements, separate dragon runs will be performed first, where firebrands will be collected in water or liquid-nitrogen pans for rapid quenching at the ejection point. The collected firebrands will be dried and fed into the dragon without ignition source, thereby providing firebrands that are cold, but with otherwise equal properties as for the reacting cases. These experiments will provide data on the non-reacting particle dispersion behavior in terms of probability density functions for trajectories, particle velocities, and particle deposition patterns, which will be used for validating the numerical framework in Task 3.2. These data sets will also allow to assess the cumulative impact of all aspects related to the combustion process on particle accumulation patters.

Task 2.4 - Analysis Statistical analysis of the quantities described above will be performed in this task. Also, to assess the effects of wind, the results obtained for the wind-driven firebrand showers will be compared with deposited firebrands in a quiescent environment as used in the ISO testing standards [29]. These experiments in a quiescent environment have in part been performed in WP1, but the parameter space will be extended here to the conditions from Task 2.2. One hypothesis is that wind impacts the heat release of deposited firebrands and the heat transfer into the fuel bed, but that a correlation between integral heat transfer and time to smoldering ignition exists independent of other parameters. If this holds, it could tremendously simplify further investigations and the development of test standards.

WP2 Milestones 1. Generate database of firebrand trajectories and velocities, deposition patterns, heat flux maps, and time to smoldering ignition for varying firebrand and flow properties. 2. Evaluate sensitivities of individual parameters and correlations between observed quantities. 3. Assess the effect of wind on deposition, heat transfer, and fuel-bed ignition.

WP3: LES of firebrands in turbulent flows

The objective of this work package is to complement the experimental study by performing high-fidelity LES of firebrand combustion in conditions matching the experiments. Simulation results will be used to validate the simulation framework for non-reacting and reacting cases, to assess the importance of firebrand-turbulence interactions, and to explain the observed sensitivities from Task 2.2. The simulations will provide quantitative data for firebrand dynamics, their interactions with turbulence, and particle dispersion in terms of trajectories and velocities. Further, ground-deposition patterns will be predicted. These results will be compared with experimental data. Predictions of heat transfer into the fuel-bed and its ignition will not be attempted in this phase.

Task 3.1 - Setting up the simulation framework using reduced-order models LES will be performed for the experimentally investigated configuration shown in Fig. 5 using boundary conditions for air flow and injected firebrands from Tasks 1.1 and 1.2. Particle trajectories, particle clustering, and dispersion caused by particle-turbulence interactions will be observed until the particles deposit on the ground. Due to the similarity of reactive firebrand dynamics with solid pulverized fuels, such as biomass [32, 68], the same validated numerical framework, including the detailed chemical kinetic models, will be employed to develop the reduced-order models required for LES. The gas-phase chemistry will be modeled using the 4D non-premixed FPV model [**E9**, 72] already available in the code. Furthermore, thermal radiation from burning firebrand, which accounts for a significant share of heat loss from the particles and affects the burnout process, will be considered. The solid kinetics will be described based on the validated models for vegetative fuels and OSB [74–77]. Particle-shape effects in particle-chemistry-turbulence interactions will be considered using the model by Fröhlich et al. [69].

Task 3.2 - Validation of simulation framework for non-reacting firebrand particles LES will be performed for non-reacting firebrands matching the conditions investigated in Task 2.3 to assess the predictive capabilities of the simulation framework for the non-reactive cases. Similar tests have been done already by Wadhwani et al. [55], albeit for a free jet instead of a wind-driven environment. The effect of firebrand rotation in later work [78] showed reasonable agreement with experiments. It is hence expected that also the present framework provides good agreement with experiments as a necessary baseline for the subsequent reactive simulations.

Task 3.3 - Parametric study and analysis of reactive firebrand dynamics using LES Multiple LES matching the experiments of Tasks 2.1 and 2.2 will be performed to investigate the impact of particle size, ejection rates, and turbulence conditions on flaming or smoldering firebrand dynamics, particle trajectories, and particle deposition rates. The predictions will first serve the purpose of validating the framework considering the effect of combustion with experimental data. Further, the evaluation of non-dimensional groups, such as particle Reynolds and Stokes numbers is straightforward in the simulations and will complement the analysis of Task 2.4. Finally, if the validation is successful demonstrating that the simulation framework can predict the parametric sensitivities observed in Task 2.3, the detailed simulation results will be used to explain the sensitivities. Otherwise, the individual single particle trajectories and their statistics, which are available from both experiment and simulation, will be used to identify the root causes of the discrepancies.

WP3 Milestones 1. Establishing the simulation framework for non-reacting and reacting firebrands considering particle shape and rotation, buoyancy, radiation, and the details of the firebrand and the gas-phase chemistry. 2. Validation of the non-reacting and reacting simulation environment. 3. Analysis of sensitivities and identification of potential areas for model improvements.

Plans for the second phase

We will extend our investigation to determine sensitivities towards firebrand and further fuel-bed materials by varying the level of devolatilization of the firebrands and considering different human-made materials, e.g., those containing flame retardants. Based on the findings from the initial gas analysis, we may integrate advanced measurement techniques, such as gas chromatograhpy [**E2**] or time-of-flight mass spectroscopy, to characterize the gas phase in more detail similar to our previous studies over a burning coal plate [**E3**]. Also model improvements for describing reacting firebrand dynamics will be developed. An important aspect will be model development for predicting heat transfer from deposited firebrand into the fuel-bed material and ignition. Further experiments for supporting the modeling activities, such as pyrometry for deposited particles, will also be performed.

Schedule

Table 1: Work program. Lower priorities tasks during overlap depicted by lighter colors.

Work packages		year 1				year 2				year 3			
WP1	Design, commissioning, and initial characterization of the wind tunnel setup												
WP2	Characterizing the impact of flow-field and firebrand properties on firebrand deposition patterns, heat transfer, and fuel-bed ignition												
WP3	LES of firebrands in turbulent flows												

The design of the experimental setup in WP1 will be be done with active participation of the Mercator fellow. During its fabrication and commissioning, the doctoral candidate will support Dr. Gauding in making necessary amendments in the simulation code in WP3. Characterization of the facility will be done in the last part of WP1, when also the data acquisition in WP2 starts. The final part of the project is dedicated to the simulations in WP3 and the joint analysis of experimental and simulation data.

2.4 Handling of research data

The handling of research data is based on the DFG guidelines for ensuring good scientific practice and follows the DFG guidelines for handling research data. The data obtained in this project will be presented at international conferences and published in recognized journals. The data sets will be adequately described and thus made available to the international research community as well as interested industry representatives, e.g., members of ISO TC92/WG14. Raw simulation data and parametric geometries will be shared upon request due to large sizes, storage, and transfer constraints. The automatic service of the IT center of RWTH Aachen University will be used allowing for automatic redundant backups, long term access, file versioning, and protection against hardware failure. Simulation results are stored in the HDF5 file format so that they can be read using a widely available open-source library. Data management plans will be created using the web-based tool Research Data Management Organizer (RDMO). For storage and distribution of research data, the research data platform COSCINE will be used. COSCINE was developed at RWTH Aachen University and allows the description of data from different sources with metadata and the definition of metadata schemes per data source to assign precisely fitting metadata. COSCINE follows the FAIR (Findable, Accessible, Interoperable, and Reusable) principles of data management. Versioning tools, such as GitLab, will facilitate the software development and data handling and will ensure reproducibility of results in collaborative settings.

2.5 Relevance of sex, gender and/or diversity

Gender and diversity aspects have no link or impact on the project.

3 Project- and subject-related list of publications

[**E1**] Hinrichs, J., Felsmann, D., Schweitzer-De Bortoli, S., Tomczak, H.-J., and Pitsch, H. “Numerical and Experimental Investigation of Pollutant Formation and Emissions in a Full-Scale Cylindrical Heating Unit of a Condensing Gas Boiler”. *Applied Energy* 229 (2018), pp. 977–989.

[**E2**] Hellmuth, M., Langer, R., Meraviglia, A., Beeckmann, J., and Pitsch, H. “The Role of C_3 and C_4 Species in Forming Naphthalene in Counterflow Diffusion Flames”. *Proc. Combust. Inst.* 40.1 (2024), p. 105620.

[**E3**] Felsmann, D., Baroncelli, M., Beeckmann, J., and Pitsch, H. “Molecular-beam mass spectrometry study of oxy-combustion in a novel coal-plate experiment”. *Proc. Combust. Inst.* 37.3 (2019), pp. 2801–2808.

[**E4**] Bariki, C., Schwenzer, C., Hesse, R., Glaznev, R., Pitsch, H., and Beeckmann, J. “A well-defined methodology to extract laminar flame speeds at engine-relevant conditions”. *Combust. Flame* 268 (2024), p. 113612.

[**E5**] Farmand, P., Nicolai, H., Schumann, C., Attili, A., Berger, L., Li, T., Geschwindner, C., di Mare, F., Hasse, C., Böhm, B., Janicka, J., and Pitsch, H. “Numerical investigation and assessment of flamelet-based models for the prediction of pulverized solid fuel homogeneous ignition and combustion”. *Combust. Flame* 235 (2022), p. 111693.

[**E6**] Desjardins, O., Blanquart, G., Balarac, G., and Pitsch, H. “High order conservative finite difference scheme for variable density low Mach number turbulent flows”. *J. Comput. Phys.* 227.15 (2008), pp. 7125–7159.

[**E7**] Farazi, S., Hinrichs, J., Davidovic, M., Falkenstein, T., Bode, M., Kang, S., Attili, A., and Pitsch, H. “Numerical investigation of coal particle stream ignition in oxy-atmosphere”. *Fuel* 241 (2019), pp. 477–487.

[**E8**] Attili, A., Farmand, P., Schumann, C., Farazi, S., Böhm, B., Li, T., Geschwindner, C., Köser, J., Dreizler, A., and Pitsch, H. “Numerical Simulations and Experiments of Ignition of Solid Particles in a Laminar Burner: Effects of Slip Velocity and Particle Swelling”. *Flow, Turb. Combust.* (2020), pp. 1–17.

[**E9**] Farmand, P., Nicolai, H., Usman, M., Berger, L., Attili, A., Gauding, M., Hasse, C., and Pitsch, H. “Modeling homogeneous ignition processes of clustering solid particle clouds in isotropic turbulence”. *Fuel* 371 (2024), p. 132054.

[**E10**] Cai, L., Kruse, S., Felsmann, D., and Pitsch, H. “A Methane Mechanism for Oxy-Fuel Combustion: Extinction Experiments, Model Validation, and Kinetic Analysis”. *Flow Turb. Combust.* (2020).

[11] Manzello, S. L., Almand, K., Guillaume, E., Vallerent, S., Hameury, S., and Hakkarainen, T. “FORUM Position Paper: The Growing Global WUI Fire Dilemma: Priority Needs for Research”. *Fire Safety J.* 100 (2018), pp. 64–66.

[12] Vacca, P., Caballero, D., Pastor, E., and Planas, E. “WUI fire risk mitigation in Europe: A performance-based design approach at home-owner level”. *J. Safety Sci. Resil.* 1.2 (2020), pp. 97–105.

[13] Taccaliti, F., Marzano, R., Bell, T. L., and Lingua, E. “Wildland–urban interface: definition and physical fire risk mitigation measures, a systematic review”. *Fire* 6.9 (2023), p. 343.

[14] Johnston, L., Blanchi, R., and Jappiot, M. “Wildland-Urban Interface”. *Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires*. Ed. by Manzello, S. L. Cham: Springer Int. Publ., 2019, pp. 1–13. ISBN: 978-3-319-51727-8.

[15] Lelouvier, R., Nuijten, D., Onida, M., Stoof, C., et al. Land-based wildfire prevention: principles and experiences on managing landscapes, forests and woodlands for safety and resilience in Europe. Publ. Office of the EU, 2021.

[16] Fernandez-Anez, N., Krasovskiy, A., Müller, M., Vacik, H., Baetens, J., Hukić, E., Kapovic Solomun, M., Atanassova, I., Glushkova, M., Bogunović, I., et al. “Current wildland fire patterns and challenges in Europe: A synthesis of national perspectives”. *Air, Soil & Water Res.* 14 (2021), p. 11786221211028185.

[17] Dupuy, J.-l., Fargeon, H., Martin-StPaul, N., Pimont, F., Ruffault, J., Guijarro, M., Hernando, C., Madrigal, J., and Fernandes, P. “Climate change impact on future wildfire danger and activity in southern Europe: a review”. *Annals Forest Sci.* 77 (2020), pp. 1–24.

[18] Suzuki, S. and Manzello, S. L. “Investigating Coupled Effect of Radiative Heat Flux and Firebrand Showers on Ignition of Fuel Beds”. *Fire Technol.* 57.2 (2021), pp. 683–697.

[19] Uhl, D. and Jasper, A. “Wildfire during deposition of the “Illinger Flözzone”(Heusweiler-Formation,“Stephanian B”, Kasimovian–Ghzelian) in the Saar-Nahe Basin (SW-Germany)”. *Palaeobiodiv. & Palaeoenv.* 101.1 (2021), pp. 9–18.

[20] Thies, B. “Machine learning wildfire susceptibility mapping for Germany” (2024).

[21] Fekete, A. and Nehren, U. “Assessment of social vulnerability to forest fire and hazardous facilities in Germany”. *Int. J. Disaster Risk Reduction* 87 (2023), p. 103562.

[22] Manzello, S. L. and Suzuki, S. “The Importance of Combustion Science to Unravel Complex Processes for Informal Settlement Fires, Urban Fires, and Wildland-Urban Interface (WUI) Fires”. *Fuel* 314 (2022), p. 122805.

[23] Santoso, M. A., Christensen, E. G., Yang, J., and Rein, G. “Review of the transition from smouldering to flaming combustion in wildfires”. *Frontiers in Mech. Eng.* 5 (2019), p. 49.

[24] Fernandez-Pello, A. C. “Wildland Fire Spot Ignition by Sparks and Firebrands”. *Fire Safety J.* 91 (2017), pp. 2–10.

[25] Manzello, S. L. “Enabling the investigation of structure vulnerabilities to wind-driven firebrand showers in wildland-urban interface (WUI) fires”. *Fire Safety Science* 11 (2014), pp. 83–96.

[26] ISO. ISO 6021:2024 - Firebrand Generator. Tech. rep. Geneva, Switzerland: Int. Org. for Standardization, 2024, p. 10.

[27] ISO. ISO/TC 92 - Fire Safety. Committee. Geneva, Switzerland: Int. Org. for Standardization, 1958.

[28] McNamee, R., Zehfuss, J., Bartlett, A. I., Heidari, M., Robert, F., and Bisby, L. A. “Enclosure fire dynamics with a cross-laminated timber ceiling”. *Fire and Materials* 45.7 (2021), pp. 847–857.

[29] ISO. ISO/TR 24188:2022 - Large Outdoor Fires and the Built Environment — Global Overview of Different Approaches to Standardization. Tech. rep. Geneva, Switzerland: Int. Org. for Standardization, 2022, p. 19.

[30] Manzello, S. L., Maranghides, A., and Mell, W. E. "Firebrand Generation from Burning Vegetation". *Int. J. Wildland Fire* 16.4 (2007), pp. 458–462.

[31] Almeida, M., Porto, L., and Viegas, D. "Characterization of Firebrands Released From Different Burning Tree Species". *Front. Mech. Eng.* 7 (2021), p. 651135.

[32] Hajilou, M., Hu, S., Roche, T., Garg, P., and Gollner, M. J. "A Methodology for Experimental Quantification of Firebrand Generation from WUI Fuels". *Fire Technol.* 57.5 (2021), pp. 2367–2385.

[33] Thomas, C. M., Sharples, J. J., and Evans, J. P. "The Terminal-Velocity Assumption in Simulations of Long-Range Ember Transport". *Math. Comput. Simul.* 175 (2020), pp. 96–107.

[34] Mendez, A. and Farazmand, M. "Quantifying Rare Events in Spotting: How Far Do Wildfires Spread?" *Fire Safety J.* 132 (2022), p. 103630.

[35] Mankame, A. and Shotorban, B. "Deposition Characteristics of Firebrands on and Around Rectangular Cubic Structures". *Front. Mech. Eng.* 7 (2021), p. 640979.

[36] Suzuki, S. and Manzello, S. L. "Investigating the Effect of Structure to Structure Separation Distance on Firebrand Accumulation". *Front. Mech. Eng.* 6 (2021), p. 628510.

[37] Nguyen, D. and Kaye, N. B. "The Role of Surrounding Buildings on the Accumulation of Embers on Rooftops during an Ember Storm". *Fire Safety J.* 131 (2022), p. 103624.

[38] Suzuki, S. and Manzello, S. L. "Role of Accumulation for Ignition of Fuel Beds by Firebrands". *Appl. Energy Combust. Sci.* 1–4 (2020), p. 100002.

[39] Meerpoel-Pietri, K., Tihay-Felicelli, V., and Santoni, P.-A. "Determination of the Critical Conditions Leading to the Ignition of Decking Slabs by Flaming Firebrands". *Fire Safety J.* 120 (2021), p. 103017.

[40] Zhu, L. and Urban, J. L. "Analyzing the Ignition Capabilities of Glowing Firebrand Accumulations". *Proc. Combust. Inst.* 40.1 (2024), p. 105746.

[41] Manzello, S. L. and Suzuki, S. "The World Is Burning: What Exactly Are Firebrands and Why Should Anyone Care?" *Front. Mech. Eng.* 8 (2023), p. 1072214.

[42] Koo, E., Pagni, P. J., Weise, D. R., and Woycheese, J. P. "Firebrands and Spotting Ignition in Large-Scale Fires". *Int. J. Wildland Fire* 19.7 (2010), pp. 818–843.

[43] Suzuki, S. and Manzello, S. L. "Experiments to Provide the Scientific-Basis for Laboratory Standard Test Methods for Firebrand Exposure". *Fire Safety J.* 91 (2017), pp. 784–790.

[44] Mensch, A. E., Wessies, S. S., Hamins, A., and Yang, J. C. "Measuring Firebrand Heat Flux with a Thin-Skin Calorimeter". *Fire Safety J.* 140 (2023), p. 103859.

[45] Bean, D. and Blunck, D. L. "Sensitivities of Porous Beds and Plates to Ignition by Firebrands". *Front. Mech. Eng.* 7 (2021).

[46] Bearinger, E. D., Hodges, J. L., Yang, F., Rippe, C. M., and Lattimer, B. Y. "Localized Heat Transfer from Firebrands to Surfaces". *Fire Safety J.* 120 (2021), p. 103037.

[47] Hakes, R. S. P., Salehizadeh, H., Weston-Dawkes, M. J., and Gollner, M. J. "Thermal Characterization of Firebrand Piles". *Fire Safety J.* 104 (2019), pp. 34–42.

[48] Suzuki, S. and Manzello, S. L. "Comparing Ignition of Fuel Beds to Firebrand Showers to Ignition of Fuel Beds by Non-Reacting Heaters". *Combust. Sci. Technol.* (2024), pp. 1–17.

[49] Prohanov, S., Filkov, A., Kasymov, D., Agafontsev, M., and Reyno, V. "Determination of Firebrand Characteristics Using Thermal Videos". *Fire* 3.4 (2020), p. 68.

[50] Bouvet, N., Link, E. D., and Fink, S. A. "A New Approach to Characterize Firebrand Showers Using Advanced 3D Imaging Techniques". *Exp. Fluids* 62.9 (2021), p. 181.

[51] Thompson, D. K., Yip, D. A., Koo, E., Linn, R., Marshall, G., Refai, R., and Schroeder, D. "Quantifying Firebrand Production and Transport Using the Acoustic Analysis of In-Fire Cameras". *Fire Technol.* 58.3 (2022), pp. 1617–1638.

[52] Bouvet, N., Wessies, S. S., Link, E. D., and Fink, S. A. "A Framework to Characterize WUI Firebrand Shower Exposure Using an Integrated Approach Combining 3D Particle Tracking and Machine Learning". *Int. J. Multiphase Flow* 170 (2024), p. 104651.

[53] Ju, X., Lisano, M., Hajilou, M., Sunderland, P. B., Stoliarov, S. I., Yang, L., and Gollner, M. J. "Quantification of Firebrand Generation from WUI Fuels for Model Development: Firebrand Generation Rate, Surface Temperature and Heat Release Rate". *Proc. Combust. Inst.* 40.1 (2024), p. 105729.

[54] Anand, C., Shotorban, B., and Mahalingam, S. "Dispersion and Deposition of Firebrands in a Turbulent Boundary Layer". *Int. J. Multiphase Flow* 109 (2018), pp. 98–113.

[55] Wadhwani, R., Sutherland, D., Ooi, A., Moinuddin, K., and Thorpe, G. "Verification of a Lagrangian particle model for short-range firebrand transport". *Fire Safety J.* 91 (2017), pp. 776–783.

[56] Tohidi, A. and Kaye, N. B. "Stochastic modeling of firebrand shower scenarios". *Fire Safety J.* 91 (2017), pp. 91–102.

[57] Mastorakos, E., Gkantonas, S., Efstathiou, G., and Giusti, A. "A hybrid stochastic Lagrangian–cellular automata framework for modelling fire propagation in inhomogeneous terrains". *Proc. Combust. Inst.* 39.3 (2023), pp. 3853–3862.

[58] Wadhwani, R., Sullivan, C., Wickramasinghe, A., Kyng, M., Khan, N., and Moinuddin, K. "A review of firebrand studies on generation and transport". *Fire Safety J.* 134 (2022), p. 103674.

[59] Wickramasinghe, A., Khan, N., and Moinuddin, K. "Determining firebrand generation rate using physics-based modelling from experimental studies through inverse analysis". *Fire* 5.1 (2022), p. 6.

[60] Kepert, J. D., Thurston, W., and Tory, K. J. "A Fast, Physically Based Model of Firebrand Transport by Bushfire Plumes". *Agricult. & Forest Meteorol.* 345 (2024), p. 109839.

[61] Mankame, A., Damiani, P., and Shotorban, B. "A computational study of the deposition of firebrands between two side-by-side blocks". *Fire Safety J.* 150 (2024), p. 104270.

[62] Manzello, S. L., Suzuki, S., Gollner, M. J., and Fernandez-Pello, A. C. "Role of Firebrand Combustion in Large Outdoor Fire Spread". *Prog. Energy Combust. Sci.* 76 (2020), p. 100801.

[63] Suzuki, S. and Manzello, S. L. "The Processes of Firebrand Deposition and Accumulation from Wind-Driven Firebrand Showers". *Fire Mater.* 47.6 (2023), pp. 827–836.

[64] Korkmaz, M., Ritter, D., Jochim, B., Beeckmann, J., Abel, D., and Pitsch, H. "Effects of Injection Strategy on Performance and Emissions Metrics in a Diesel/Methane Dual-Fuel Single-Cylinder Compression Ignition Engine". *Int. J. Engine Res.* 20.10 (2019), pp. 1059–1072.

[65] S. Kruse, J. Beeckmann, J. Casas, and H. Pitsch. "The effect of altering Lewis numbers by hydrogen addition on flame speed and structure of laminar and turbulent CH_4 flames - An experimental study". *Eur. Combust. Meet.* 2017.

[66] Beeckmann, J., Hesse, R., Schaback, J., Pitsch, H., Varea, E., and Chaumeix, N. "Flame propagation speed and Markstein length of spherically expanding flames: Assessment of extrapolation and measurement techniques". *Proc.Combust. Inst.* 37.2 (2019), pp. 1521–1528.

[67] Farazi, S., Attili, A., Kang, S., and Pitsch, H. "Numerical study of coal particle ignition in air and oxy-atmosphere". *Proc. Combust. Inst.* 37.3 (2019), pp. 2867–2874.

[68] Filkov, A., Prohanov, S., Mueller, E., Kasymov, D., Martynov, P., Houssami, M. E., Thomas, J., Skowronski, N., Butler, B., Gallagher, M., Clark, K., Mell, W., Kremens, R., Hadden, R. M., and Simeoni, A. "Investigation of Firebrand Production during Prescribed Fires Conducted in a Pine Forest". *Proc. Combust. Inst.* 36.2 (2017), pp. 3263–3270.

[69] Fröhlich, K., Farmand, P., Pitsch, H., Meinke, M., and Schröder, W. "Particle Reynolds number effects on settling ellipsoids in isotropic turbulence". *Int. J. Multiphase Flow* 139 (2021), p. 103566.

[70] Seoud, R. and Vassilicos, J. "Dissipation and decay of fractal-generated turbulence". *Physics of fluids* 19.10 (2007).

[71] Tomboulides, A., Lee, J., and Orszag, S. "Numerical simulation of low Mach number reactive flows". *J. Scientific Comp.* 12.2 (1997), pp. 139–167.

[72] Nicolai, H., Debiagi, P., Wen, X., Dressler, L., Massmeyer, A., Janicka, J., and Hasse, C. "Flamelet LES of swirl-stabilized oxy-fuel flames using directly coupled multi-step solid fuel kinetics". *Combust. Flame* 241 (2022), p. 112062.

[73] Cai, Y., Tay, K., Zheng, Z., Yang, W., Wang, H., Zeng, G., Li, Z., Boon, S. K., and Subbaiah, P. "Modeling of ash formation and deposition processes in coal and biomass fired boilers: A comprehensive review". *Applied Energy* 230 (2018), pp. 1447–1544.

[74] Debiagi, P., Pecchi, C., Gentile, G., Frassoldati, A., Cuoci, A., Faravelli, T., and Ranzi, E. "Extractives Extend the Applicability of Multistep Kinetic Scheme of Biomass Pyrolysis". *Energy & Fuels* 29.10 (2015), pp. 6544–6555.

[75] Debiagi, P., Gentile, G., Cuoci, A., Frassoldati, A., Ranzi, E., and Faravelli, T. "A predictive model of biochar formation and characterization". *J. Analyt. & Appl. Pyrol.* 134 (2018), pp. 326–335.

[76] Gong, J., Zhu, H., Zhou, H., and Stoliarov, S. I. "Development of a pyrolysis model for oriented strand board. Part I: Kinetics and thermodynamics of the thermal decomposition". *J. Fire Sci.* 39.2 (2021), pp. 190–204.

[77] Gong, J. and Zhang, M. "Pyrolysis and autoignition behaviors of oriented strand board under power-law radiation". *Renewable Energy* 182 (2022), pp. 946–957.

[78] Damiani, P., Mankame, A., and Shotorban, B. "Modeling of firebrand dispersion and deposition in turbulent jet flows". *13th U. S. National Combustion Meeting*. College Station, Texas, USA. 2023.

4 Supplementary information on the research context

4.1 Ethical and/or legal aspects of the project

4.1.1 General ethical aspects

Not applicable.

4.1.2 Descriptions of proposed investigations involving humans, human materials or identifiable data

Not applicable.

4.1.3 Descriptions of proposed investigations involving experiments on animals

Not applicable.

4.1.4 Descriptions of projects involving genetic resources (or associated traditional knowledge) from a foreign country

Not applicable.

4.1.5 Explanations regarding any possible safety-related aspects

Not applicable.

4.1.5.1 “Dual Use Research of Concern”; foreign trade law

Not applicable.

4.1.5.2 Risks in international cooperation

Not applicable.

4.1.6 Considerations on aspects of ecological sustainability in the planning and implementation of the project

While combustion experiments will be performed during the project, the total amounts of burnt material will be comparably low. Most of the energy will be required to run the wind tunnel. Hence, a special effort will be made to purchase an energy-efficient fan driving the tunnel. Furthermore, simulations will be used to support the analysis of the experiments, which leads to a substantially smaller experimental test matrix. All simulations will be performed with a highly efficient code and strategies will be investigated to minimize the computational cost per simulation.

4.2 Employment status information

Prof. Dr.-Ing. Heinz Pitsch, Director of Institute for Combustion Technology, RWTH Aachen University, permanent position

Dr.-Ing. Dipl.-Wirt.-Ing. Joachim Beeckmann, Senior Research Associate at Institute for Combustion Technology, RWTH Aachen University, permanent position

4.3 First-time proposal data

Not applicable.

4.4 Composition of the project group

Prof. Heinz Pitsch will supervise the simulation part of the project.

Dr. Joachim Beeckmann will supervise the experimental work in the project.

Dr. Michael Gauding (Senior research associate, Institute for Combustion Technology, RWTH Aachen University, permanent employment, university funding) leads the simulation group at ITV. He will perform a part of the proposed simulation work and support the doctoral researcher.

Dr. Hongchao Chu (Scientific Staff, Institute for Combustion Technology, RWTH Aachen University, temporary employment, university funding) is group leader for combustion applications at ITV. He will extend the simulation framework and support the proposed simulations and analysis.

Dr. Maximilian Hellmuth (Scientific Staff, Institute for Combustion Technology, RWTH Aachen University, temporary employment, university funding) will contribute his expertise in the design and setup of the experimental facility.

A product designer and a technician with permanent employment at ITV will support the project with university funding.

4.5 Researchers in Germany with whom you have agreed to cooperate on this project

None.

4.6 Researchers abroad with whom you have agreed to cooperate on this project

Not applicable.

4.7 Researchers with whom you have collaborated scientifically within the past three years

Prof. A. Cuoci, Politecnico di Milano, Italy - Prof. M. Pelucchi, Politecnico di Milano, Italy - Prof. H. Curran, NUI Galway, Ireland - Prof. M. Mansour, American University in Cairo, Egypt - Prof. B. Dally, KAUST, Saudi Arabia - Prof. M. Sarathy, KAUST, Saudi Arabia - Prof. A. Attili, University of Edinburgh, UK - Prof. S. Kang, Sogang University, Sount Korea - Prof. A. Jocher, TU Munich, Germany - Prof. U. Maas, Karlsruhe Institute of Technology, Germany - Dr. N. Chaumeix, ICARE Orleans, France - Prof. L. Cai, Tongji University, China - Prof. A. Parente, ULB Brussels, Belgium - Dr. G. Linteris, NIST, USA - Prof. S. Kaiser, Universität Duisburg-Essen, Germany - Prof. T. Kaspar, Univesity Paderborn, Germany

- Prof. A. Kempf, Universität Duisburg-Essen, Germany - Prof. C. Hasse, TU Darmstadt, Germany - Prof. A. Dreizler, TU Darmstadt, Germany - Prof. J. Janicka, TU Darmstadt, Germany - Prof. W. L. Roberts, KAUST, Saudi Arabia - Prof. F. Creta, University of Rome, Italy - Prof. G. J. Nathan, University of Adelaide, Australia - Prof. F. Halter, ICARE Orleans, France - Prof. M. E. Mueller, Princeton University, USA - Prof. R. Sandberg, University of Melbourne, Australia - Prof. J. F. MacArt, University of Notre Dame, USA - Prof. S. Esposito, University of Bath, UK - Prof. T. Grenga, University of Southhampton, UK - Prof. A. Bardow, ETH Zürich, Switzerland - Prof. F. di Mare, University of Bochum, Germany - Prof. B. Chen, Shanghai Jiaotong Unviersity, China - Prof. B. Böhm, TU Darmstadt, Germany - Prof. V. Chenadec, Gustave Eiffel University, France - Prof. H. Schmid, University of Paderborn, Germany - Dr. N. Chaumeix, CNRS-ICARE Orleans, France - Prof. Chiara Galletti, University of Pisa, Italy

4.8 Project-relevant cooperation with commercial enterprises

Not applicable.

4.9 Project-relevant participation in commercial enterprises

Not applicable.

4.10 Scientific equipment

The ITV has access to the Claix cluster at RWTH Aachen University via the NHR Alliance for high-performance computing. The NHR Alliance combines resources and expertise of high-performance computing and makes them available to scientists at German universities. The Claix cluster has a total number of 632 nodes, each equipped with two Intel Xeon 8468 Sapphire CPUs. For performing the numerical simulations relevant to this project, a compute time proposal will be submitted to NHR.
The ITV has specialized facilities for conducting combustion experiments and owns various gas sensors. The testo 350 - Analysis Box for exhaust gas analysis systems is already equipped with O_2, CO, CO_2, NO_2 sensors. The GC from Agilent Technologies, Inc. (model 6890N) is equipped with a mass-selective detector (model 5975C), thermal conductivity detector, and flame ionization detector. It quantifies H_2, O_2, N_2, CO, CO_2, and HC ranging from C_1-C_{16}. The GC is complemented by a storage system consisting of a gas measurement system (GMS, Teckso GmbH) mounted on a wagon. The GMS can collect and store up to 16 gaseous samples in sample loops at a constant temperature. The mobility of the storage system allows for sample collection at GC-offsite locations, e.g., other rooms or buildings. The ABB gas analyzers include sensors for total unburned HC (Fidas 24); O_2 (Magnos 206); CO and CO_2 (Uras 26); and NO, NO_2, and NO_x (Ecophysics CLD 700el). The Cambustion exhaust emission instrumentation determines emissions of total unburned HC (HFR500, 1 ms response time) and NO_x (CLD500, 2 ms response time).

4.11 Other submissions

Not applicable.

4.12 Other information

Not applicable.

5 Requested modules/funds

5.1 Basic Module

∑ Total Basic Module requested funds (simulation, PI Pitsch)	**138,554 €**
∑ Total Basic Module requested funds (experiment, PI Beeckmann)	**204,304 €**

5.1.1 Funding for Staff

To achieve the project objectives, one research assistant of special scientific qualification is required, who will be responsible for the project processing. Within the framework of the research project, the research assistant will have the possibility to do a Ph.D. in the corresponding subject area. The execution of the work packages requires support by student assistants.

Doctoral researcher 50 % (E13 II, 3 years) (simulation)	40,800 €/year
Doctoral researcher 50 % (E13 II, 3 years) (experiment)	40,800 €/year
Student assistant 50 % (10 h/week, 3 years) (simulation)	4,134.66 €/year
Student assistant 50 % (10 h/week, 3 years) (experiment)	4,134.66 €/year

∑5.1.1 (simulation)	**134,804 €**
∑5.1.1 (experiment)	**134,804 €**

5.1.2 Direct Project Costs

∑5.1.2 (simulation)	**3,750 €**
∑5.1.2 (experiment)	**24,500 €**

5.1.2.1 Equipment up to Euro 10,000, Software and Consumables

To set up the measurement equipment, the acquisition of the following items is required.

Thermocouples	Type K thermocouples and wiring	4,000 €
Thin skin calorimeters	ASTM E459-22	4,000 €
Optics	Cameras and accessories	6,750 €
	Subtotal (experiment)	**14,750 €**

Consumables include fabricated firebrand materials and window replacements. It further includes the cost for the proximate and ultimate analyses.

Year 1:	Consumables	2,000 €
Year 2:	Consumables	3,000 €
Year 3:	Consumables	1,000 €
	Subtotal (experiment)	**6,000 €**

5.1.2.2 Travel Expenses

The scientific results achieved in the project will be presented at national and international conferences (Int. Combustion Symposium, European Combustion Meeting, Numerical Combustion Meeting, European Symposium on Fire Safety Science, International Symposium on Fire Safety Science) to increase the visibility of the project and to enable scientific exchange. For participation fees, travel, and accommodation costs, 2,500 €/year are requested.

∑5.1.2.2 (simulation)	**3,750 €**
∑5.1.2.2 (experiment)	**3,750 €**

5.1.2.3 Visiting Researchers (excluding Mercator Fellows)

Not required.

5.1.2.4 Expenses for Laboratory Animals

Not required.

5.1.2.5 Other Costs

Not required.

5.1.2.6 Project-related Publication Expenses

Not required.

5.1.3 Instrumentation

∑5.1.3 (experiment)	**45,000 €**

5.1.3.1 Equipment exceeding € 10,000

To set up the wind tunnel, the acquisition of the following items is required.

Pre-condition unit	Fan, control unit, flow straightener, strut profiles, adapters, plates	19,000 €
Test section	Strut profiles, adapters, plates, windows, hinge joints	13,500 €
Post-condition unit	Strut profiles, adapters, plates, atomizing-spray unit, drain	9,500 €
RWTH Dragon	Conveyor, control unit	3,000 €
	Subtotal (experiment)	**45,000 €**

5.1.3.2 Major Instrumentation exceeding € 50,000

Not required.

5.2 Module Temporary Position for Principal Investigator

Not required.

5.3 Module Replacement Funding

Not required.

5.4 Module Temporary Clinician Substitute

Not required.

5.5 Module Mercator Fellows

∑ Total Module Mercator Fellows requested funds 109,200 €

The PIs of the project have expertise in computational and experimental combustion, turbulent flows, reacting multiphase flows, solid-fuel combustion, and combustion theory, which are all relevant for the project. However, both have not actively worked on wildfires or WUI fires. This domain expertise and the connection to the international fire research community will be added to the project by Prof. Samuel L. Manzello (Institute of Fluid Science, Tohoku University, Japan and Reax Engineering, USA, based in Japan). His active participation in relevant international organizations and working groups for ISO standards will bring international visibility to the project and provide an impactful outlet for the research results.

Prof. Manzello is an outstanding and world-renowned scientist bridging the gap between WUI fires and fundamental combustion science. He is a combustion scientist who has made great strides in applying combustion knowledge to WUI fires. As a world-renowned expert in WUI fires, he was, e.g., an invited speaker and panelist at The Chemistry of Urban Wildfires - A Virtual Information-Gathering Workshop hosted by the National Academies of Science, Engineering, and Medicine in 2021. The firebrand generator, known as the Dragon, which he invented, was published as an international standard by ISO TC92, Fire Safety, 2024, and will be used in this project. As the convener of ISO TC92/WG14 (Large Outdoor Fires and the Built Environment Working Group) and co-leader of the International Association for Fire Safety Science (IAFSS) permanent working group LOF&BE (Large Outdoor Fires and the Built Environment), which are groups with more than 250 global members, he has strong academic, government, and industrial ties. His experimental expertise will be invaluable in setting up and coupling the RWTH Dragon with the wind tunnel, and conducting the experimental campaigns in this project. He will be able to introduce new work items for the global ballot as the project develops key technical findings on firebrand processes that are urgently needed for global standardization. As a Mercator Fellow, Prof. Manzello will be continuously involved in the project and will spend three months per year at RWTH Aachen University. He also plans to participate in our annual project meetings.

Travel air fare per year	2,500 €/year
Accommodation rent for three months per year	3,000 €/year
Compensation (DFG rate, 10.300 € per month) for three months per year	30,900 €/year

5.6 Module Workshop Funding

Not required.

5.7 Module Public Relations Funding

Not required.

5.8 Module Standard Allowance for Gender Equality Measures

Not required.