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# ZONAL MODEL VALIDATION FOR AN ENVIRONMENTALLY FRIENDLY AIRCRAFT CARGO FIRE PROTECTION SYSTEM WITH CONTAINERIZED LOAD

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## Abstract

Today's cargo bays use halon as fire suppression agent. However, due to the high ozone depletion potential of this chemical, alternative solution are researched. Within this framework, the cargo bay in the Fraunhofer Flight Test Facility has been equipped with a nitrogen based fire suppression system to investigate the local distribution of oxygen and nitrogen concentrations. This paper focusses on the system performance when empty or loaded with geometrically equivalent LD3 container elements that replicate the flow blockage for the fire suppression agents in the cargo hold. Furthermore, the test data is used to validate a zonal model predicting the local distribution of agents in the cargo hold. This simulation tool has been developed within the CleanSky2 Environmentally Friendly Aircraft Cargo Fire Protection System.

**Keywords:** Cargo fire suppression, halon replacement, Flight Test Facility, zonal modelling

## 1. Introduction

A homogeneous and efficient fire suppression agent distribution inside an aircraft cargo hold is the key for protecting the aircraft from a cargo hold fire and for achieving the fire protection goals. Aircraft cargo hold fire suppression systems must provide fire protection for several hours. Thus the system must be adequate to maintain a safe fire suppressive atmosphere inside the cargo hold for the specified diversion time.

The aircraft cargo fire suppression system has a dual phase of fire suppression, a fire knockdown phase that shall diminish fire either by cooling or starvation as described in the Minimum Performance Standard (MPS) [1], followed by the constant metering phase to maintain fire suppressive environment inside the cargo hold throughout the flight and landing phase. In current aircrafts, both phases (i.e. knockdown phase and constant metering phase) are performed by halon bottles. A quantity of halon from bottles is released to perform the knockdown within two minutes and then the fire suppressive environment is maintained within the cargo hold by constant metering of halon. However, due to high ODP of halon, industry evolves towards halon free systems. The use of nitrogen as a suppression agent, diluting the cargo hold oxygen concentration below flammability point, is one such alternative.

In the following sections, a developed simulation toolchain is presented that predicts the agent concentration distribution within the cargo hold. For model validation, a nitrogen based knockdown and holding system has been integrated in the Flight Test Facility aircraft mock-up. The cargo hold has been loaded with LD3 sized cardboard containers and equipped with sensors to measure the local oxygen concentration. A realistic cabin pressure profile of take-off, cruise and descent is implemented. For this, the aircraft is located in a low pressure vessel that is able to generate an ambient pressure like in cruise conditions (750 hPa, corresponding to an equivalent height of 8.000 ft.). This paper summarizes the following cargo configurations:

- Empty cargo hold
- 100% loaded cargo hold: 10 LD3 sized containers inside the cargo hold

The knock down is performed using standard industrial nitrogen bottle bundles. For the holding phase an OBIGGS (On-Board Inert Gas Generation System) technology demonstrator provides Nitrogen Enriched Air (NEA). Such apparatus already today is in aeronautical use for fuel tank inerting [2] and selectively separates the incoming airflow into a nitrogen-rich fraction (NEA) and an oxygen rich fraction dumped overboard.

## 2. Method

The following sections describe the simulation method applied as well as the experimental method.

### 2.1 Indoor Environment Simulation Suite (IESS)

The Indoor Environment Simulation Suite (IESS) provides indoor climate simulation using the zonal approach [3]. In contrast to CFD or multi-zone models, the zonal modelling approach subdivides the indoor space into typically $10^2$ to $10^3$ zones [4]. In addition to this airflow modelling, the IESS provides interfaces for walls, sources and sinks, radiation, conduction and species distribution. Through this, a transient, multiphysics simulation is enabled. A toolchain has been developed to ease the setup, customization and post-processing of the models [5]. The IESS uses hybrid simulation approach, where high momentum flow regime close to nozzle discharge has been pre-simulated by CFD and the results of this near-field domain have been integrated with the zonal model of the cargo hold [6]. The IESS provides an effective option for transient simulations with local resolution and good simulation accuracy.

Figure 1 highlights the model building process. Starting from a CAD file, the Model Generator, a self-developed script creates a geometrically correct zonal model of the interior space including the long-wave radiation view factor matrix, adjacencies of air zones and walls, sources' and sinks' location and so called CFD-zones for the highly entrained airflows. These CFD zones are similar to an air inlet boundary condition and parametrized from pre-performed CFD simulations. All this information is exported as ready to execute Modelica code. In the modelling environment Dymola, boundary conditions are set and the simulation is conducted. In the post processing, such data is arranged as transient concentration color plots.

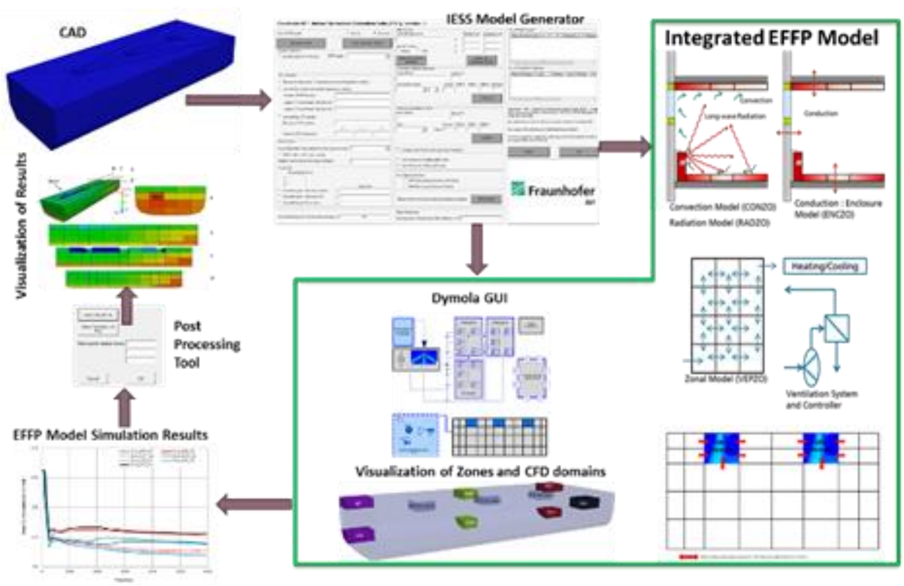


Figure 1: Indoor Environment Simulation Suite (IESS)

## 2.2 Test environment

Experiments were conducted in the wide-body mock-up of the Flight Test Facility (FTF) located at the Fraunhofer Institute for Building Physics in Holzkirchen, Germany. A schematic view of the FTF is presented in Figure 2. The front part of a former in service twin-aisle long range aircraft containing cabin, crown, galley, cockpit, avionics bay, cargo and bilge is placed in a low pressure vessel. Through the variation of the pressure in the vessel, the cabin pressure evolution of a real flight can be simulated. The mock-up is equipped with a ventilation system to replicate the ECS. In order to generate a similar heat load in the cabin, thermal dummies are placed on the seats. Through this, a realistic airflow pattern in the cabin is ensured. Recirculation air is aspired from the triangle area and exhaust air is ejected from the bilge. Hence, a realistic air flushing around the cargo hold is ensured.

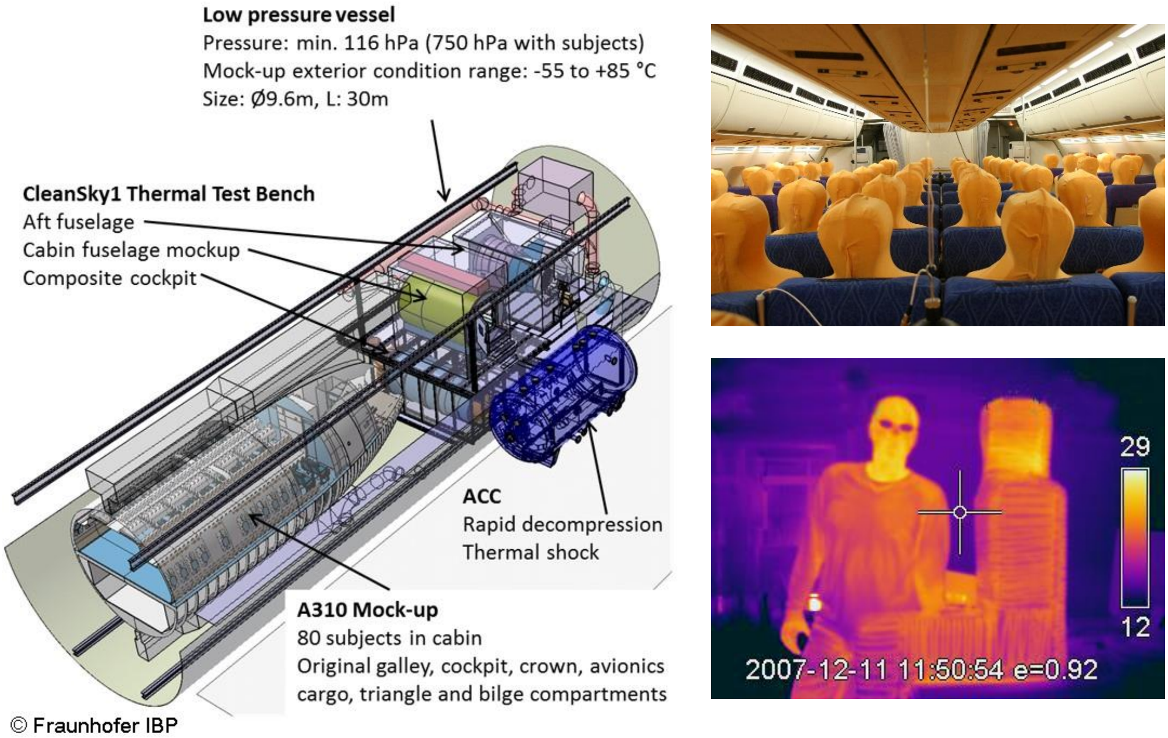


Figure 2: Overview of the Flight Test Facility, cabin equipped with thermal dummies and IR-picture of human compared to dummy

## 2.3 Cargo bay refurbishment

For the environmentally friendly fire protection system tests, the cargo bay was refurbished (Figure 3, left). The main items of the refurbishment are:

- Original lining and ceiling panels from ordered spare parts and A350 production series (except the center line, where Plexiglas was used to keep the agent distribution line visible)
- Sealing to meet state of the air airtightness requirements
- Integration of high pressure piping and injection nozzles with protective cavity in the ceiling
- Integration of the pressure management system allowing for the equalization of pressure between cargo bay and adjacent bays to avoid opening of rapid decompression panels during knockdown and descent.
- Cargo door leakage simulation according to the MPS standard [1] to simulate the airflow leaking through the door seal in flight
- Distributed oxygen concentration measurement to assess the local distribution.

The nitrogen needed to perform the inerting task was taken from industrial bottles placed outside the low pressure vessel. The bottles were on a scale to measure the consumed amount of nitrogen. Furthermore, an On-Board Inert Gas Generating System (OBIGGS, Figure 3, right) demonstrator, derived from the fuel tank inerting technology, has been integrated in the flight test facility. The OBIGGS consists of selective air separation membranes that separate hot pressurized air into a nitrogen rich fraction used for cargo bay inerting and an oxygen rich fraction dumped overboard.

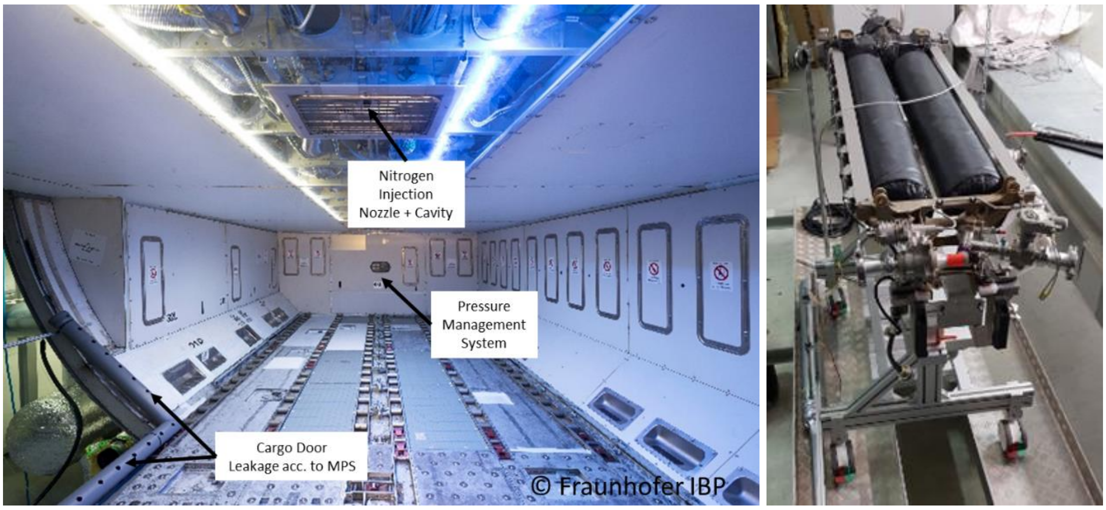


Figure 3: Refurbished cargo hold (left) and integrated OBIGGS (right)

Sensor placement is shown in Figure 4. To measure the oxygen concentration FCX-MC25-CH sensors with an accuracy of ±0.5 % within the range 0-25 % $O_2$, O2S-FR-T6-LG 1918 from SST and PAROX Paramagnetic $O_2$ Gas Analysers were used.

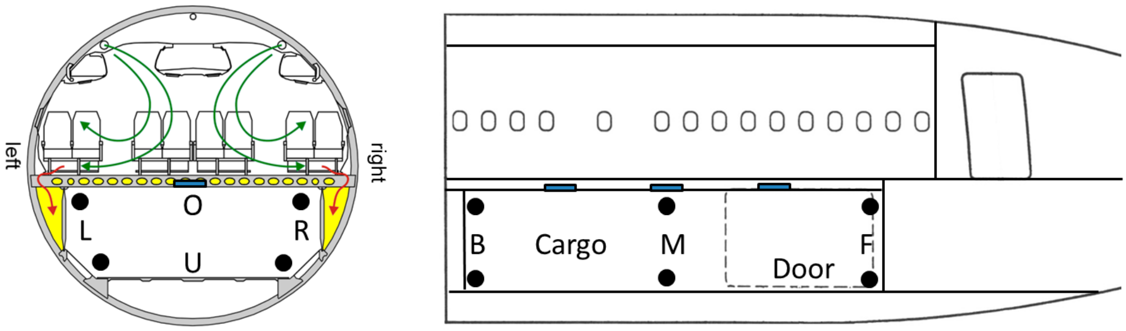


Figure 4: Sensor placement

For the containerized cargo tests, LD3 sized containers are built from cardboards. These containers are sealed with tapes and plastic foils to ensure their air tightness (Figure 5). The oxygen concentration sensors were relocated into the 2 inch gap between containers and sidewalls.

Figure 5: Containerized cargo hold during integration (left) and 100% loaded (right)

## 2.4 Test conduct

At the beginning of the test, heat dummies in the cabin and the cabin ventilation system are turned on. Then, the pressure in the low pressure vessel is reduced from ambient pressure to 750 hPa (8000 ft.). The leakage flow simulation through the cargo door is activated. Due to this suction, air from the underfloor area enters the cargo bay through leakages in the enclosures. When pressure, airflow rates and temperatures are stabilized, the test begins:

- Phase 1: Knockdown
  A large amount of nitrogen is supplied in a short timeframe to bring down the oxygen concentration in the cargo hold
- Phase 2: Holding
  A metered flow of nitrogen enriched air provided from an On-Board Inert Gas Generating System (OBIGGS) is supplied. This flow compensates for fresh air ingress through cargo leakages
- Phase 3: Descent
  The descent phase is critical in terms of oxygen concentration due to the repressurization from 750 hPa to ground pressure. This repressurization is performed by supplying ambient air. Thus, a noticeable amount of fresh air enters the cargo hold and increases the oxygen concentration. There are two strategies to cope with this, either the holding system increases its flow accordingly or the oxygen concentration is kept sufficiently low prior to descent to meet the requirement at end of descent.

For model validation, the test sequence set out in Table 1 was performed. The conduct simulates a normal flight where the fire suppression system gets activated until landing at the airport.

Table 1: Performed test sequence

| Test | Empty cargo hold | 100% (10 LD-3 containers) |
|---|---|---|
| Cargo Air Volume (estimated) | 57,6 m³ | 14.8 m³ |
| Knock-Down discharge | 62.5 kg in 250 s | 41 kg in 244 s |
| NEA supply rate | 9 l/s, starting after completed knockdown | 8.6 l/s |
| Holding time | 19 min | 26 min |
| Descent time | 10 min | 11 min |
| Cargo cruise pressure | 750 hPa | |

## 3. Test results

In this section, the test results are presented.

### 3.1 Pressure profile

The pressure profile is shown in Figure 6. The test starts as a “normal flight” by reducing the pressure from ground to cruise pressure of 750 hPa. After a flow and temperature stabilization phase, the knock-down and holding system were activated. This does not translate into a noticeable change of cabin pressure. The descent is simulated by gradually increasing the cabin pressure to ground conditions.

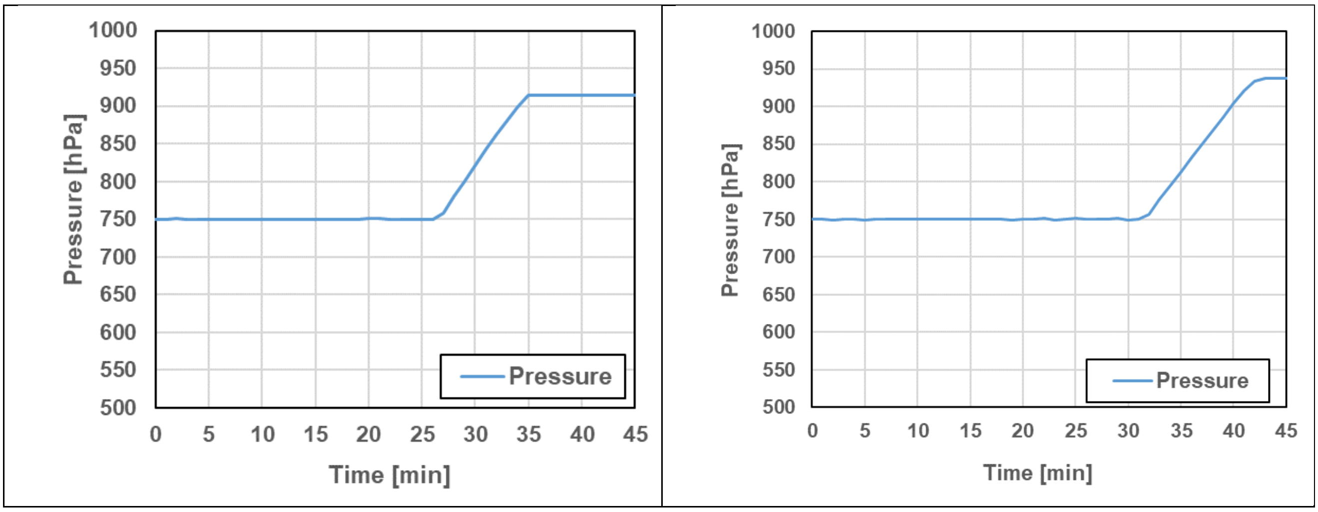


Figure 6: Pressure profile of empty cargo hold (left) and 100% loading (right)

### 3.2 Oxygen concentration profile

Figure 7 compares the transient cargo concentration profiles for the empty cargo hold. After knock-down, a concentration of 6% oxygen is achieved in the cargo hold. During the holding phase, the NEA operation limits the increase of oxygen concentration to 8%. In descent, the ingress of air to repressurize the cargo results in an additional increase of oxygen concentration in the cargo hold to a final level of 10%. From analysis of the door extraction data, it is likely that part of the air to repressurize the cargo hold was flowing inversely and thus was blown on sensor MUR. Therefore, it is thinned and dotted in the plot. A local leakage could have impacted BUR sensor.

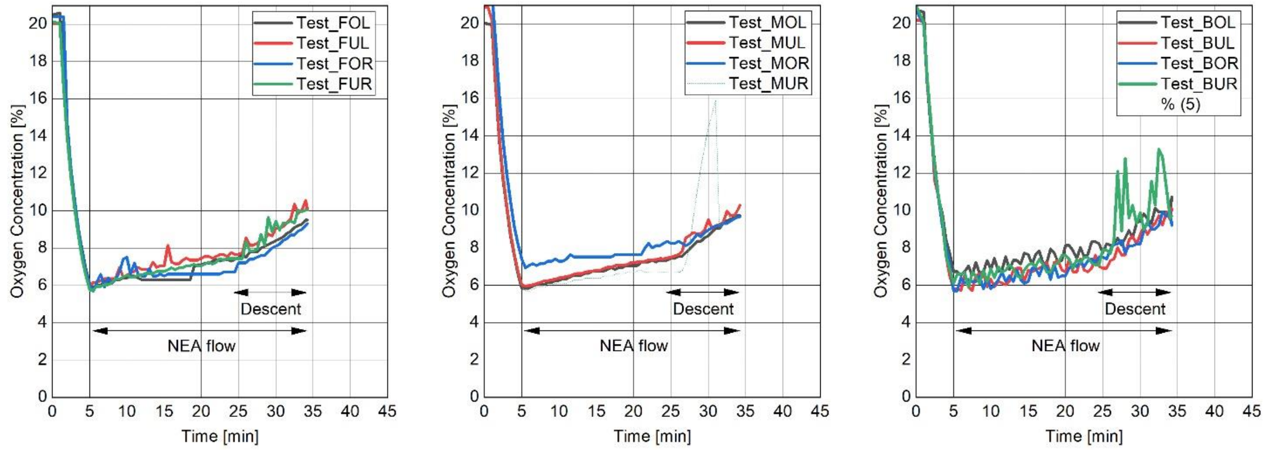

Figure 7: Oxygen concentration profile of empty cargo hold front, middle and back cut

Figure 8 shows the concentration profiles for the loaded case. Gaps in the data are due to partial short-time failure of the pumped $O_2$-sampling occurring for sensors FOL, MUL, MOR and BUR. During knock-down, the oxygen concentration rapidly drops to 0% or max. 5%. After, despite the use of NEA, the concentration quickly rebuilds again due to the air ingress compensating for the door seal leakage simulation. Local concentrations vary between 8.8% and 16.6% during the cruise phase and further increase during descent.

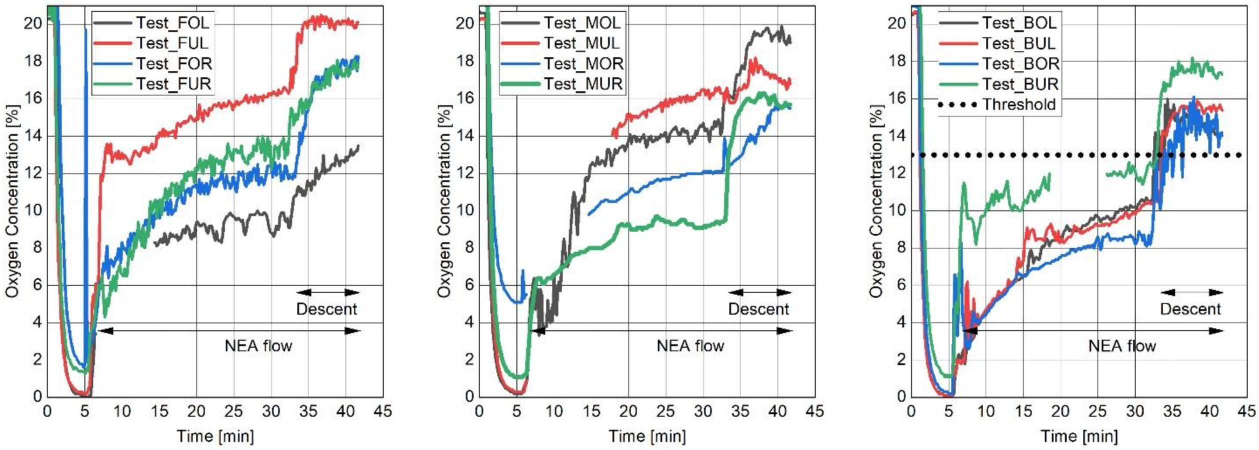


Figure 8: Oxygen concentration profile of loaded cargo hold front, middle and back cut.

## 4. Model validation

The flow rates set out in Table 1 and the pressure profile (Figure 6) are used as a boundary conditions for the simulation model. The shape of the generated zonal models for the cargo air volume is shown in Figure 9. Zones used for comparison to measurements are marked blue and with three letters according to their location (Back-Middle-Front, Under-On top, Left-Right). It is obvious that the containerized case results in very flat zones compared to the unloaded case.

Air is modelled to ingress the cargo hold through the pressure management system located on the rear wall (Figure 3) and to leave through the door seal.

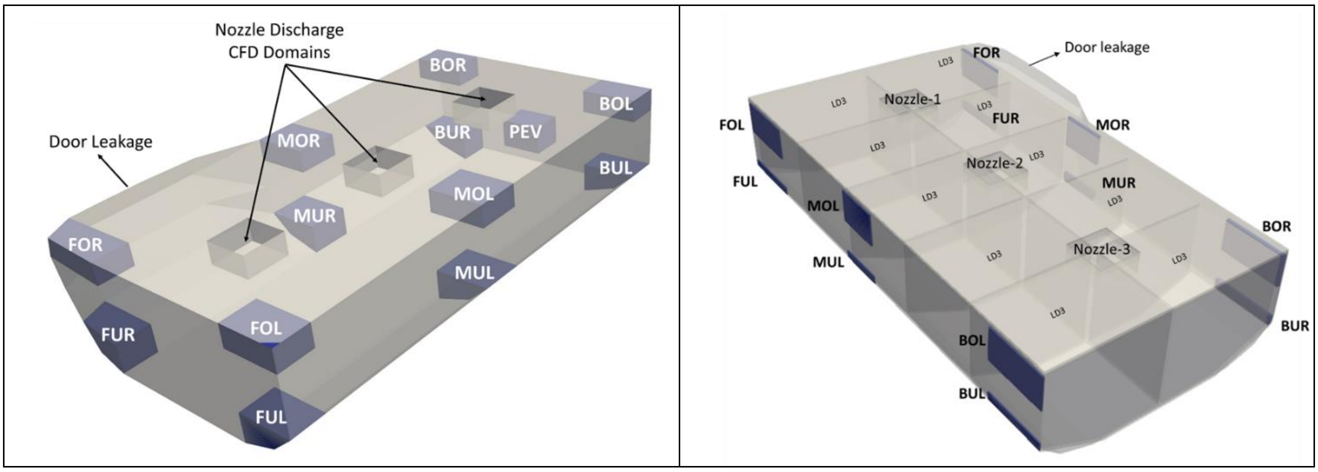


Figure 9: Generated zonal cargo hold models for empty cargo (left) and containerized cargo (right)

## 4.1 Validation of the empty cargo hold

The comparison between simulation and measurement shows that the accuracy of the model is consistently within 1% oxygen concentration. The only major exception from this are sensors MOR (impacted by fresh air ingress in the test) and BUR. The sensor BUR shows a high fluctuation during descent in the test, wherefore it is not sure whether some local leakage may have dominated the air ingress here. The lower readings of the sensor are in line with the simulation.

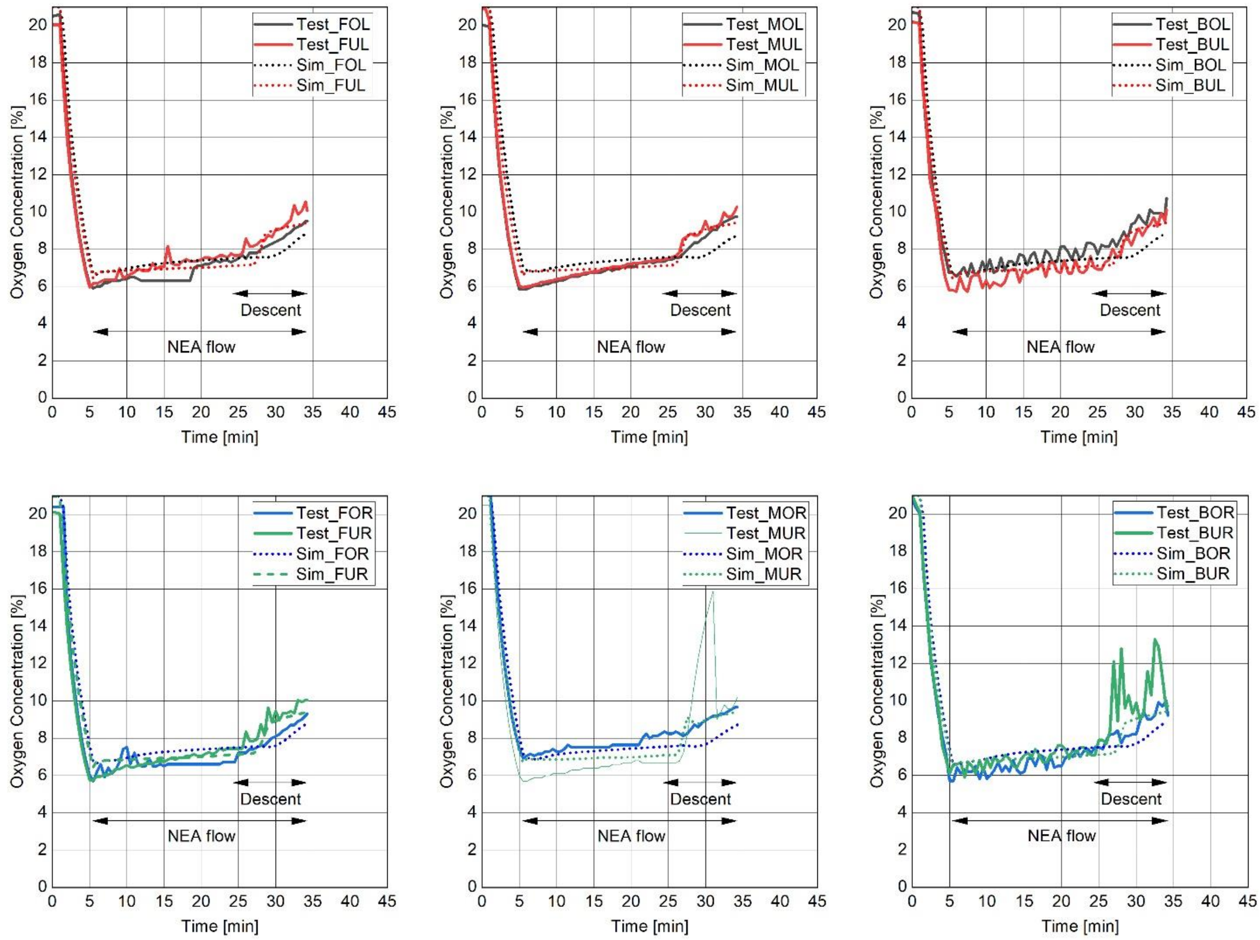


Figure 10: Validation results for the empty cargo hold

## 4.2 Validation of the loaded cargo hold

The comparison between simulation and measurement shows that some positions well correlate (FOL, BOL, BUL, FOR, MUR, BOR), whereas other positions differ by several percent in oxygen concentration (FUL, MOL, MUL, FUR, MOR, BUR). The concentration dynamic response is well predicted with the simulation (Figure 11).

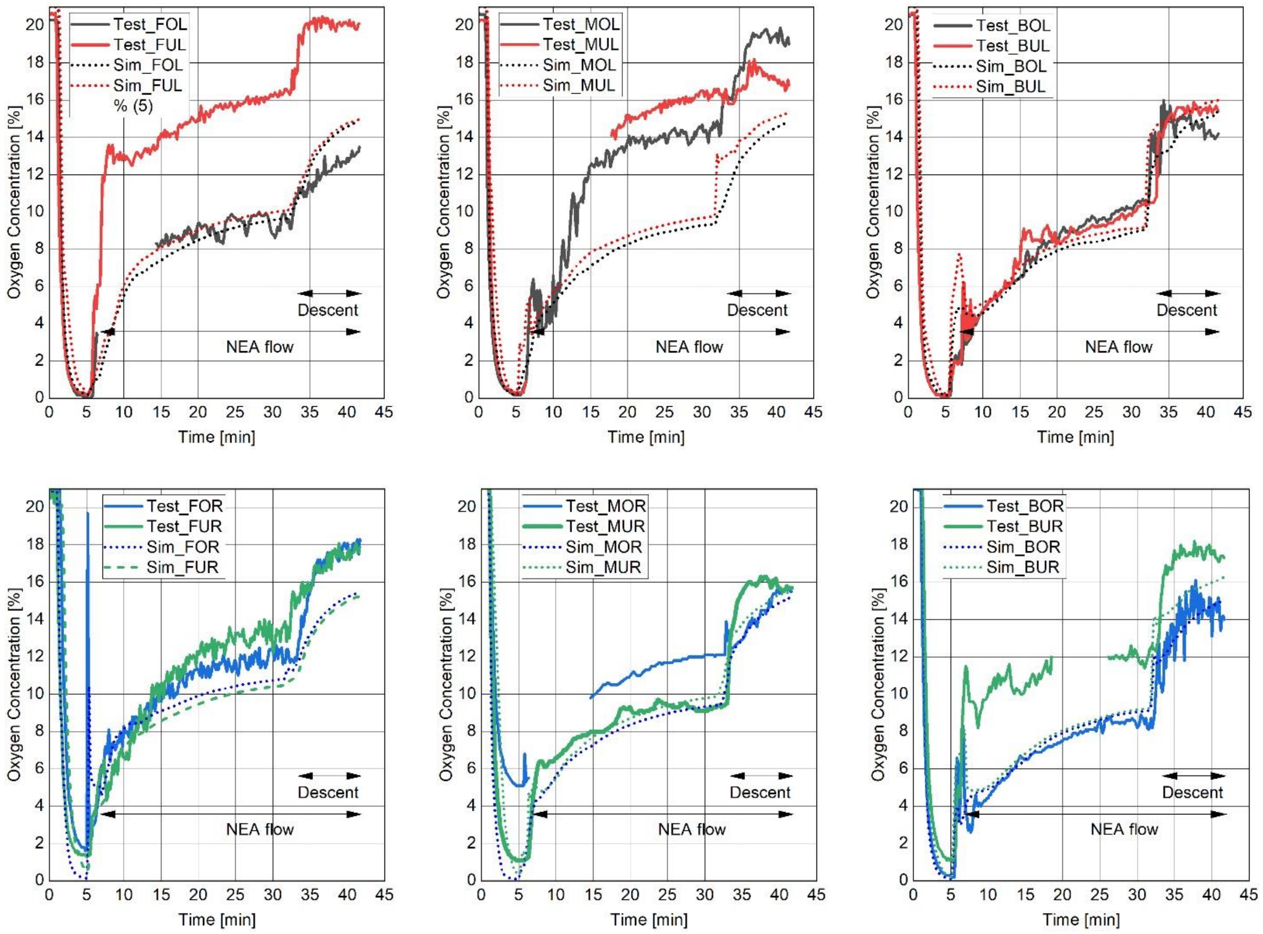


Figure 11: Validation results for the loaded cargo hold front, middle and back

The simulation assumes the sidewalls to be perfectly airtight and the only air ingress to occur through the pressure management system. Hence, unpredictable local leakages are not implemented in the model. In order to assess the model's ability to predict the maximum concentration in the cargo hold, the zone concentration adjacent to the modelled air ingress is compared with sensor FUL, where highest concentrations were measured. It can be seen, that the model predicts the final maximum oxygen concentration well, however the profile slightly varies. This could be due to the fact that even other leakages in the test setup contribute to the fresh air ingress (Figure 12).

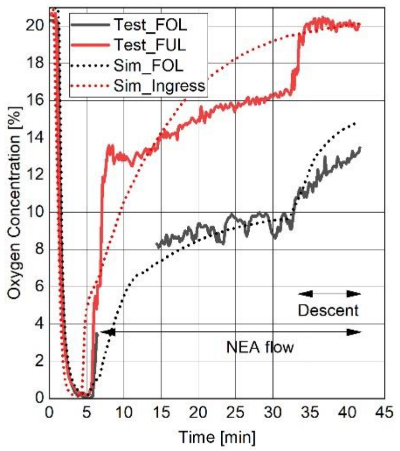


Figure 12: Comparison of modelled maximum concentration

## 5. Discussion

Despite the higher nitrogen mass injected into the empty cargo hold, the larger volume of the empty cargo leads to a higher initial oxygen mass of 6% after knock-down compared to 0% to max. 5% for the fully loaded case.

The measurement data further show that the loading in the cargo hold results in a system with much higher dynamics than the empty cargo hold. Two main effects are assumed to contribute to this effect. On one hand, the step response of a system depends on its inertia, which in the case of concentrations is the volume in which species mix. The empty cargo hold has a 3-9 times higher air volume than the loaded cargo and hence, any step changes of the system only translate with a comparably higher time delay and lower magnitude. As a result, the loaded cargo hold reaches a very low oxygen concentration after a relatively short time, but once the flow of pure nitrogen stops, oxygen concentration rebuilds relatively fast, too.

On the other hand, the ability of air to mix impacts the systems local inertia and distribution. In the empty cargo hold, air has a good ability to mix and hence level out any step response whereas in the loaded case, small gaps between the containers are only weakly interconnected potentially resulting in poorly ventilated zones. If a leakage of fresh air ingresses into the cargo hold close to one of the sensors, the lack of mixing together with the smaller volume the sensor is representative of result in a higher impact. As a result, the high gradient of concentration profile emerges.

In terms of model validation, it becomes obvious that the global trend of cargo bay concentrations can be well predicted with the zonal model. However, flaws like leakages in the test setup, or, thinking further, in the actual installation may lead to local deviations from this ideal behavior. In the test, care was taken to seal the panels and leakages were actively sought taped if detected [7]. Still, a certain amount of leakage apparently prevailed. Furthermore, for the loaded case, the low inertia and thus highly dynamic response of concentrations together with weak and somehow random connections between volumes and leakages, make an accurate simulation very hard. Nevertheless, the simulation model overall predicts the concentration evolution and maximum concentrations.

In this test setup, the containers were entirely wrapped with foil to be close to airtight. It is expected that they emptied and filled up with air according to the pressure change with the flight profile, but once at stabilized pressure condition, they are no source or sink of additional fresh air. How realistic this assumption is should be further evaluated. Typical LD3 containers are made of aluminum and are used multiple times, thereby getting buckled and hard treated. Whether they fulfil the same level of airtightness is questionable. Furthermore, the load transported in the container may impact on the available air volume.

## 6. Conclusion

This paper shows a comparative test and model validation for an empty cargo and a loaded cargo test case when using nitrogen as environmentally friendly fire suppression agent to replace halon. Overall, the model is able to predict the concentration profile with an accuracy of 1% oxygen concentration in the unloaded case.

For the loaded test condition, the local distribution of non-controllable leakages makes the accurate prediction of cargo hold oxygen concentration gradients a challenge, but the model well predicts the trends and maximum concentrations.

The modelling approach proves valid to perform system sizing and the orchestration of the different fire suppression phases knockdown and holding. For the future workflow, it is suggested to use the developed model to design the system and to finally verify it in the Flight Test Facility prior to performing flight tests. The correct replication of containerized load should be further investigated to assess how representative an airtight container is or whether exchange and storage effects of container air volumes may impact the result.

## 7. Acknowledgements

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## 8. Copyright Statement



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