Performance-Based Fire Safety Design of Cold Storages

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ABSTRACT
This paper will present a study on the fire behaviour in cold storages based on correlations, numerical fire models and other information currently available on the topic. The main parameters that affect the fire behaviour in cold storages will be discussed, such as ambient temperatures, different types of storage configurations, types of stored products and packaging. The paper will also present fire load data associated with different cold storage types and discuss practical solutions and design methods that can be applied in the fire safety design of cold storages. The aim of the paper is to identify gaps in the current knowledge of fire behaviour in cold storages, and to discuss to what extent the research and tests that have been carried out for normal warehouse storages are adaptable to cold storage fire studies. Limitations of the available numerical and analytical models will be discussed, such as the need for validated input parameters and the computational resources needed for advanced modelling. Finally, the need for further research, testing and model validation will be pointed out.

INTRODUCTION
Cold storages can accommodate large quantities of valuable goods and high fuel loads due to densely arranged solid-pile and high-rack storage configurations. Although the probability of fire may be low in this type of occupancy, cold-storage fires may result in significant property losses. Frozen storage products in high volume spaces with limited openings to the outside result in complicated fire dynamics that is a challenging topic for the fire safety engineer in pursuing the most economic design without jeopardizing safety.

Significant research and large scale testing on general warehouse fires can be found in the literature, e.g. studies on in-rack fire plume flow conditions, the effect of ESFR sprinklers, the effect and configuration of in-rack sprinklers and more. [1][2][3] Limited research and testing has been carried out that is aimed specifically at cold storage or frozen storage fires, despite the very different conditions with regards to fire behaviour and significant property losses due to cold storage fires in the past. [4] The storage of valuable food products of great magnitude in a single compartment presents a significant source of risk, to which a proper fire safety design is a key element in limiting the possible damage and achieving an acceptable level of safety.

The challenging issue in performance based fire design of cold storages is variation in use over time and determining the design assumptions regarding fire load densities and operations carried out within the relevant building. Refrigerated storages associated with processing facilities can generally be assumed to have a stable inventory in terms of product types and storage configuration. This allows more detailed and less conservative assumptions to be made in the fire safety design. Refrigerated warehouses can be categorized based on the storage temperatures and types of products stored, ranging from coolers and chill rooms at approximately -5 to 5 °C for storage of chilled food products, to freezers at -20 to -30 °C for the storage and blast freezing of frozen food products. This paper will mainly focus on the latter,
as conditions in refrigerated storages at temperatures around zero °C are considered closer to that found in general warehouse storages. The risk associated with refrigerant media in cold storages is largely out of the scope of this paper.

**FIRE LOAD IN COLD STORAGES**

The fire load in cold storages can be very significant when considering the entire quantity of combustible materials within the compartment. However, studies on fires in cold storages have suggested that where frozen products are kept, a proportion of the fire load is protected and will not be involved in fire or contribute well to fire spread [5]. The most extreme examples of this are densely arranged piles of palettes with block frozen fish, where no air gap exists between the frozen product and the packaging as ice takes up all the extra void. In this case fire spread occurs on the exposed surface and the fire does not penetrate the storage pile easily. The ratio of protected fire load needs to be assessed individually, depending on storage configuration, type of goods stored and so forth.

The fire load associated with the storage of frozen food products is mainly due to packaging materials. Combustible materials in cold-storage warehouses include mainly wooden pallets, cardboard packaging, plastic wrapping and other packaging materials. Insulated sandwich panels with combustible core material also need to be accounted for in the fire load density estimation, as this can vary significantly from non-combustible mineral wool core to highly combustible polystyrene. The stored product itself imposes less fire risk, although this depends on what type of product is being stored. The net heat of combustion of materials, $H_u$ [MJ/kg], can be expressed by Eq. 1 [6], where $u$ [%] is the moisture content by dry mass and $H_{u0}$ [MJ/kg] is the net calorific value of the dry material. [6] In terms of fish or meat products, the moisture content can be significant. The moisture content of fish can be close to 80 %. This leaves only 20 % of dry material and with combustion efficiency taken into account, the effective fire load associated with fish products will be very limited. In many cases it can be omitted from the fire load density in the compartment.

$$H_u = H_{u0} (1 - 0.01 \cdot u) - 0.025 \cdot u \quad (1)$$

Estimation of the fire load density in a building or a fire compartment should account for all combustible items expected within the compartment. However, the involvement of the combustible products in fire can be taken into account. In some cases it can be demonstrated that a part of the fire load is protected and will not be involved in fire. Eq. 2 shows how the total unprotected fire load density can be calculated, where $q_{up}$ and $q_{i,p}$ are the fire load density in MJ/m² for the unprotected and protected combustible materials, respectively. $\Psi_{p,i}$ is the ratio of protected combustible material $i$. [6]

$$q = q_{up} + \sum_i \Psi_{i,p} \cdot q_{i,p} \quad (2)$$

Furthermore, the incomplete combustion of materials can be taken into account, EN 1991-1-2 states that for mostly cellulosic materials, the combustion efficiency can be assumed 80 %. Fig. 1 illustrates how an effective fire load can be determined based on the categorization of materials discussed above.
Table 1 and Fig. 2 show data from eight case studies of frozen storages where fire load densities have been determined based on the assumptions and procedures discussed above. Some of the storages were associated with a process, but others are refrigerated warehouses where more error is included in the fire load data due to variation in use. The fire load density is based on inventory information from each storage owner/user over a limited period to determine the composition of the stock, types of materials and packaging. The floor area utilization referred to in table 1 represents how much of the total floor area is designated for the storage of materials, the remainder of space is reserved for access routes for forklifts etc. All the case studies involved constructions with insulated sandwich panels with combustible polyisocyanurate insulation core (PIR). In all cases the panels had a fire rating B-s2,d0 according to the EN 13501-2 standard. [7]

Table 1: Case studies for frozen storage fire load densities.

<table>
<thead>
<tr>
<th>Occupancy</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
<th>Case 5</th>
<th>Case 6</th>
<th>Case 7</th>
<th>Case 8</th>
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</thead>
<tbody>
<tr>
<td>Product type</td>
<td>Frozen fish</td>
<td>Frozen fish</td>
<td>Frozen fish</td>
<td>Frozen fish</td>
<td>Frozen fish</td>
<td>Frozen fish</td>
<td>Frozen fish</td>
<td>Frozen foods</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Palletized piles</th>
<th>Palletized racks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building materials</td>
<td>Steel structure with insulated sandwich panels with PIR core</td>
<td></td>
</tr>
<tr>
<td>Floor area [m²]</td>
<td>1995</td>
<td>1314</td>
</tr>
<tr>
<td>Ceiling height [m]</td>
<td>9.0</td>
<td>8.5</td>
</tr>
<tr>
<td>Floor area utilization [%]</td>
<td>77</td>
<td>83</td>
</tr>
<tr>
<td>Max no. of pallets</td>
<td>5328</td>
<td>2832</td>
</tr>
</tbody>
</table>

As Fig. 2 shows, the total combustible fire load density in the storages varies from 2 – 9000 MJ/m² and the effective fire load ranges from 900 – 1800 MJ/m². The assumed protected fire load is therefore significant based on this analysis. The fire load density calculation and assumptions made for the combustion efficiency and protected fire load is dependent on justifications based on other fire safety aspects in each relevant storage. This includes the implementation of smoke ventilation that limits temperatures and fire spread. This affects the involvement of sandwich panels with combustible insulation and protects combustible materials within the storage piles.
The case studies only contain data for one frozen storage with normal frozen foods (case 8), instead of frozen sea products. This storage included products such as frozen meals, pizza, bread, vegetables and fruit. The composition of the stock was based on inventory data from the respective client over a limited period. A variation between product categories was conservatively assumed, as consumer habits and market conditions may change the composition of the stock.

A statistical analysis is needed with a larger group of case studies, to effectively determine a storage utilization distribution to be able to determine a design fire load density based on a relevant statistical quantile. For the purposes of the current analysis, the calculated fire loads are conservatively based on the assumption that the storage space is fully utilized and the storage composition was determined based on inventory data over a short period. The utilization error was assumed to compensate for the possible unsafe assumption in product composition in the storage.

**FIRE DYNAMICS IN COLD STORAGES**

Cold storages generally have large volumes, relatively high fuel loads (in total) and limited openings to the outside. The magnitude of a fire may therefore be limited by the lack of oxygen supply, but this can also cause unburned combustion products to accumulate in the building. This can cause increased risk, e.g. for the fire brigade when doors are opened and more oxygen is suddenly supplied to the fire.

Fire spread and fire growth are significantly dependent upon the density, heat capacity and thermal conductivity of solid fuels, as well as the ambient temperature. In frozen storages, the ambient temperatures can be as low as -30 °C. For stored products such as block frozen fish, where no air gap exists between the frozen product and the packaging, a lot of energy is consumed while heating the surface of the packaging. Firstly, this may affect the critical ignition point of the material and the ignition delay time, which affects mainly the fire spread and fire growth in the frozen storage. Secondly, this may affect the burning rate of the material due to conductive heat losses to the frozen material behind the exposed surface, therefore decreasing the heat release rate of the fire.
To further explain the effect of frozen water within a burning solid, Fig. 4 shows the main heat transfer mechanisms of a typical control volume. [7] The figure shows the energy transported in and out by oxygen diffusion ($\dot{q}_o''$) and the energy transported by solid and gaseous fuel ($\dot{q}_s''$ and $\dot{q}_f''$, respectively). $\dot{q}_{CND}$ is the energy transported by conduction and $\dot{q}_{RAD}$ represents the radiative energy absorbed by the material. Finally, $\dot{q}_g''$ is the heat generated or absorbed by a chemical reaction within the material, which is relevant to the current analysis due to the endothermic process of melting and evaporating the water within a frozen product.

Based on Fig. 4, Eq. 3 is derived that describes the change in energy within the control volume as a function of time and location within the solid ($t$ and $x$, respectively). [7] The first and second term within brackets on the right hand side of the equation represent energy coming into and going out of the control volume, respectively.

$$\frac{\partial E_{CV}}{\partial t} = $$

$$[\dot{q}_s''(x^+, t) + \dot{q}_f''(x^+, t) + \dot{q}_0''(x, t) + \dot{q}_{CND}(x, t)] - $$

$$[\dot{q}_s''(x, t) + \dot{q}_f''(x, t) + \dot{q}_0''(x^+, t) + \dot{q}_{CND}(x^+, t)] + $$

$$\dot{q}_{RAD}(x, t)dx + \dot{q}_g''(x, t)dx$$  (3)

This shows that the water content of frozen fuels can be assumed to have a negative effect on the temperature development within the solid and therefore delay the pyrolysis process that leads to ignition and flaming combustion of the fuel. Quantifying how this affects fire spread and burning of materials, without the use of advanced modelling or testing, is very challenging and bound to some restrictions in accuracy and use for practical design purposes. Further discussions regarding the relationship represented by Eq. 3 can be found in the SFPE handbook. [7]

Based on the assumption of thermally thick material, the time to ignition may be expressed according to Eq. 4. Where $k$ [W/mK] is the thermal conductivity, $\rho$ [kg/m$^3$] is the material density and $c$ [J/kgK] is the specific heat of the material. $T_{ig}$[K] and $T_{ao}$[K] are the critical ignition temperature of the material and ambient temperature, respectively. $\dot{q}_a$[kW/m$^2$] is the applied heat flux. [7] Other relationships can be found that illustrate that the flame spread rate across solid fuels is inversely correlated with the $kpc$ parameter ($V \propto 1/kpc$). [8] An increased
value of the parameter $k_{pc}$ therefore extends the time to ignition and decreases fire spread, giving further credence to the assumptions described before.

$$t_{ig} = \frac{\pi k_{pc}(T_{ig} - T_{so})^2}{q_e^2}$$  \hspace{1cm} (4)$$

Fig. 4 shows the ignition delay time, $t_{ig}$ [s], as a function of applied heat flux, $q_e$ [kW/m²], according to Eq. 4. To understand what effect the density and other material properties have on ignition, two different sets of material properties were assumed. Firstly, the material is assumed to have a uniform property that may represent a low density product in cardboard and plastic packaging, with $k_{pc} = 144 \text{ W}^2 \text{s}/\text{m}^4\text{K}^2$. Secondly, the material is assumed to have a more dense property that may represent block frozen fish in cardboard and plastic packaging, with $k_{pc} = 339 \text{ W}^2 \text{s}/\text{m}^4\text{K}^2$. Fig. 4 illustrates how increasing the $k_{pc}$ parameter significantly affects the ignition of materials according to Eq. 4.

![Figure 4: Ignition delay times as a function of heat flux.](image)

Another aspect, in addition to the delayed ignition time and reduced fire spread, is to what extent the frozen products affect the burning rate of the surface of exposed packaging materials. The mass loss rate of materials $\dot{m}''$ [kg/m²s] can be expressed by Eq. 5. Where $\dot{Q}''_{\text{flame}}$ [kW/m²] and $\dot{Q}''_{\text{external}}$ [kW/m²] are the heat from flames and from an external heat source, respectively. $\dot{Q}''_{\text{losses}}$ [kW/m²] is the heat loss from the material and $L_v$ [kJ/kg] is the necessary energy to change the material into flammable gas. Based on this, the mass loss rate of the exposed thin packaging may be reduced as a result of conductive heat losses to the solid block of frozen product that forms a heat sink.

$$\dot{m}'' = \frac{\dot{Q}''_{\text{flame}} + \dot{Q}''_{\text{external}} - \dot{Q}''_{\text{losses}}}{L_v}$$  \hspace{1cm} (5)$$

Concluding from the above, the endothermic process of melting and evaporating water in frozen storage products can be considered to delay the pyrolysis process that leads to flaming combustion of the fuel and reduce fire spread and the mass burn rate of the material. Based on this, fire growth in frozen storages can be considered to be relatively slow compared to normal warehouse conditions. Other aspects like the air humidity in frozen storages may also affect the fire dynamics. The dry air may cause the packaging materials to have less moisture content that may induce fire spread on the external surface. Not much focus is given on this aspect in the current analysis, but its existence should be noted.
NUMERICAL MODELLING OF COLD STORAGE FIRES

Computational Fluid Dynamics (CFD) fire models are commonly used in performance-based fire safety design of buildings. Most commonly a prescribed design fire is used, so the model is only used to determine smoke spread and temperature, but not to predict fire spread or the burning behaviour of materials. Modelling the reaction of burning materials has two main issues, namely, lack of computing power and the accuracy and quality of the input parameters. Direct application of complex pyrolysis modelling in design needs to be done with care, as it relies on many unsupported assumptions for input parameters and constants. In some cases, a simple modelling method can be more accurate than a complex method with inadequate assumptions and input parameters.

Fig. 5 shows a model comprising of one continuous pair of palettes with frozen products, fire spread and burning is simulated using a material reaction model. The objective is to capture the effect of highly dense frozen food products on fire spread across the external packaging. Fire simulations are carried out by implementing the CFD code Fire Dynamics Simulator (FDS) by the National Institute of Standards and Technology (NIST). [9] The model takes into account the relevant thermal properties of the materials and other principles of fire dynamics incorporated in the combustion and fluid flow models of FDS. Simulations are carried out with a number of different assumptions for the material properties governing the fire behaviour of materials. These include the thermal conductivity, density, specific heat capacity and also parameters and constants for the pyrolysis reaction model in FDS, such as the reference temperature and heating rate.

Figure 5: Simulated fire spread over a surface in a 3D fire model including a material reaction model.

Two main simulation cases were carried out. The first one assuming a solid with uniform material property representing a normal pallet with food products and packaging, e.g. frozen pizza in cardboard boxes. The second simulation case was carried out assuming a thin layer of cardboard packaging on the outside and a block of highly dense material on the inside, representing typical thin cardboard packaging for block frozen fish. In the second case, ignition was delayed by 900 seconds compared to the first case, fire spread was very limited and the fire was not self-sustained. It was found that variation in the input parameters could significantly change the results, limiting the reliability of the results as the input parameters are bound to uncertainties. Therefore it was concluded that, without reference to further research and testing, the results could not be used directly for design purposes. But these results further support to the conclusions made before regarding the fire behaviour of frozen products, compared to normal conditions. The conclusions that can be drawn from the simulations is that in the case of block frozen fish, compared to normal products in similar packaging, the ignition delay time will be increased and fire spread will be more limited.

For the purposes of this analysis, it was decided to incorporate a prescribed fire curve for each individual pallet surface into a large model with 150 pallets. The fire spread between pallets was determined by incorporating the relationship between heat flux and ignition delay times presented in Fig. 4. The individual design fire curves for the models were determined based on a model with a single pallet with a prescribed burning rate and “fast” fire growth according to
EN 1991-1-2 [10] to obtain an HRR curve for each pallet surface. Based on that simulations, the fire duration for a pallet with block frozen fish is approximately 20 minutes, whereas a pallet with other typical food products has a 50 minute fire duration.

Simulations are carried out for two different storage configurations, a palletized pile storage and a palletized rack storage. The critical heat flux and ignition delay times vary based on the material properties of the stored product, to predict fire spread between palettes. Two different analyses are carried out for a rack storage configuration, one with block frozen fish and another with normal refrigerated storage product with less density and different burning behaviour. The stacking height is 6.5 m in a palletized pile case, but 8.0 m in the rack configuration.

![Figure 6: HRR-time curves based on fire simulations for 150 pallets.](image)

Fig. 6 shows the fire curves for the three cases, furthermore the fire spread and burning in each of the models is shown in table 2. Note that the model assumes no obstruction to oxygen flow to the fire, therefore the total HRR is only dependent on the fuel, contrary to what could happen in a real fire scenario in a storage room with very limited openings to the outside. The simulated fire curves in Fig. 6 are compared to a slow, medium and fast fire growth curves according to a simple expression, \( Q = \alpha t^2 \), where \( Q \) is the heat release rate of the fire, \( \alpha \) is a fire growth parameter and \( t \) represents time. Fig. 6 shows that the fire growth rates for the three different cases vary from close to a “slow” growth rate for block frozen fish to almost a “fast” growth rate in the case with less dense storage products in racks.

The fire curves in Fig. 6 show that based on the assumptions and input parameters discussed, the type of products stored and storage configuration can significantly affect the fire behavior in the compartment. In the case with normal refrigerated storage product in a rack storage configuration, the fire growth and the maximum HRR is significantly greater than in the case with block frozen products in a storage rack. The frozen fish in a palletized pile storage configuration gives the smallest fire growth rate and the smallest HRR. This illustrates well the importance of incorporating the appropriate storage conditions into the design work to obtain a safe and economic fire safety design.
Table 2: Palletized rack and palletized pile storage fire spread.

<table>
<thead>
<tr>
<th>Sharp freezer storage – block frozen fish – Palletized piles</th>
<th>Sharp freezer storage – genuine products – Palletized racks</th>
<th>Sharp freezer storage – block frozen fish – Palletized racks</th>
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DESIGN IMPLEMENTATION

The regulatory environment in many countries now allows performance-based fire safety design of buildings. In contrast with a fire safety design based on prescriptive requirements. In this way, the designer is enabled to optimize the fire safety design for each project based on fire loads, size and type of building and other relevant parameters. Simulations and calculations can be carried out to illustrate that the design satisfies clearly defined performance requirements. If carried out according to best practice, performance-based design should give a much clearer image of the available level of safety, compared to prescriptive design.

By taking into account the special conditions in frozen storage facilities described earlier, calculations can be carried out to obtain the most economic design while retaining an acceptable level of safety. This includes determining the need for structural fire protection, smoke ventilation, escape routes, fire compartments, material use and so forth. The following subchapters give a short overview of practical implementation and equipment selection for fire safety in frozen storages.

Fire detection and alarm system

Ordinary fire detection equipment is generally not suitable for the cold environment found in cold storages and frozen storages. The use of aspirating smoke detection systems is considered the most appropriate for these conditions. In which case a central detection unit, located outside the cold storage, draws air through a network of pipes inside the storage compartment to sample air and detect smoke particles.

Sprinkler system

Implementing sprinkler systems in cold storages is a challenging task in terms of design and construction and in terms of operation, maintenance and testing of the systems. As these types of rooms or buildings are generally large, the use of carbon dioxide or foam systems are not considered suitable. Generally a combined dry pipe and pre-action systems need to be used. Considerations are needed to prevent ice plugs and the location and temperature rating of sensors needs to ensure sprinkler response close to that of a wet pipe system. Design calculations presented in this paper show that for certain categories of frozen storages, sprinkler systems are not necessary to ensure an acceptable level of safety. However, this depends highly on the storage size, configuration and type of materials being stored.

Building material use

Large frozen storages are genuinely structural steel constructions with insulated sandwich panels. The insulation requirement is very high in these types of buildings and U-values close to 0.1 W/m²K are not uncommon. To achieve this low U-value, the use of sandwich panels with combustible plastic insulation cores are feasible due to their high insulating properties. Those types of panels are also lighter and can span further between supports. The use of insulation cores that melt and spread fire rapidly, such as expanded polystyrene (EPS), is not allowed according to many standards and regulations. The main materials allowed to use in insulated sandwich panels are Polysiocyanurate (PIR), Polyurethane (PUR) and Mineral wool (MW). Mineral wool has the best fire performance of the three, but the poorest economic properties in terms of U-values, weight etc. Polysiocyanurate gives in general a better performance in terms of fire spread, smoke development and burning than polyurethane insulated panels. This may vary between products depending on the composition of the insulation core, the construction of the panel, fixing and joint finishing etc.
The use of sandwich panels with combustible insulation cores causes certain risk with regards to fire. The major effects of fire causing risk related to insulated panel elements in cold storages is the collapse of the insulating panel system due to fixing failure, hidden fire spread behind panels and delaminating of the steel sheet from the insulation as the steel expands and the bonding heats up, exposing the insulation core to the fire with increased heat release rates and smoke production. [11][12] The reaction to fire classification and fire resistance classifications strongly rely on the joint finishing, span length, fastenings and panel orientation. Some PIR panels can be obtained with reaction to fire rating B-s1,d0 according to EN 13501 [11] with special joint sealing. The fixing and span lengths need to be according to the classification documents supplied by the panel manufacturer, carried out by an independent laboratory.

**Refrigerant leak detection and emergency equipment**
The refrigerating systems in large storages generally have direct systems with R717 refrigerant (ammonia). Ammonia is extremely toxic, flammable and can cause explosion risk. The risks associated with refrigerants need to be taken into account. Appropriate measures should be taken to ensure the safety of people, including the implementation of an ammonia detection system, emergency ventilation, response planning and selecting electrical equipment for the use in environments where explosive atmospheres can form (ATEX).

**Smoke ventilation**
Depending on the fire safety design, the smoke ventilation in a cold storage can play an important role in satisfying performance criteria for property protection and safety of people. The smoke ventilation can limit temperatures, maintain a sufficient smoke free height and provide visibility. Wall mounted natural smoke ventilation openings are commonly used on cold storages. As the conditions in cold storages are very specialized, the selection of equipment needs to be done with care. It has proven difficult to obtain suitable equipment for frozen storages, as the classifications according to EN 12101-2 do not cover this type of occupancy. Special considerations include using motors and struts that can be used in the cold environment, thermally broken frames and perimeter heat cables to prevent icing of the frame and hinges and the vent freezing shut, insulated panel. Similar provisions need to be made for the openings for the exhaust and openings for the inlet air.

**Other fire safety precautions**
The performance of equipment needs to be ensured in case of fire, for example by using heated door frame elements to ensure safe escape routes in case of fire, ammonia leakage or another hazard. Other fire safety and fire protection issues need to be addresses, such as escape routes, emergency lighting, manual extinguishing equipment, structural fire resistance, maintenance and response planning and more.

**CONCLUDING REMARKS**
The paper has presented a methodology for the performance-based fire safety design of cold storages based on numerical fire models. The paper has demonstrated how fire simulations with complex material reaction models can be used to help with determining and justifying assumptions regarding fire spread and fire growth parameters. The design assumptions can then be incorporated into a larger fire model to determine the need for fire safety measures in cold storages. By applying the calculations and methods discussed here to a frozen storage fire safety design, significant optimization can be achieved compared to the prescriptive regulatory requirements in many countries. The implementation of the fire design and the selection of equipment needs to account for the special conditions in cold or frozen environments.
Based on the simulations carried out and a review of the available theory and information on real fires in refrigerated warehouses, it can be concluded that fire spread and heat release rates can be significantly affected by the conditions found in refrigerated storages, especially frozen storages. However, there is need for further research and testing to support the assumptions drawn from the information currently available. More knowledge is needed into the effects of frozen products on ignition, fire spread, burning rates and combustion efficiency. Studies are needed on how the heating and phase changes of frozen water inside the frozen product affect fire spread and burning of packaging material at the external surface. Further research and testing can help to increase safety and property protection while inducing more economic fire safety designs for this type of buildings.

REFERENCES