# Enclosure Fire Temperatures: Experimental Evidence and Standard Time-temperature Curves

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## ABSTRACT

From large-scale explosion testing it has been seen that the overpressure is controlled mainly by three factors: stoichiometry and mixing, congestion leading to increased turbulence and scale. Enclosed fires are controlled by the same factors. However, for enclosed fires the result is not so much an increase in pressure as it is an increase in temperature. Numerous experiments with pool, spray and jet fires with hydrocarbons have been conducted in both enclosures and in the open, and at different scales. Most of these tests result in temperatures that are expected and are referred to in the literature. However at some configurations we have measured temperatures exceeding what were expected for the test setup.

**KEYWORDS:** Enclosure fire, large fire, time-temperature curve, scaling.

## BACKGROUND

In hazard evaluations, the impact of a fire is often quantified by a heat flux density towards an object (kW/m$^2$), and this heat flux density is used as an input to calculations of heat load to external objects as well as objects embedded in the flames and the fire plume. It is also used to calculate the evaporation rate of liquid pool fires and is an important factor in assessment of fire dynamics. An extensive summary of research in the area of thermal radiation from large fires is contained in the chapter of the Society of Fire Protection Engineers (SFPE) Handbook, entitled Fire Hazard Calculations for Large Open Hydrocarbon Fires [1].

In this summary, a statement about thermal radiation which is commonly used in the literature is given: For fires greater than a few meters in diameter, the effective emissivity of the flame can be taken as one. In other references like the NIST Report 6546 [2], this statement is: For fires greater than a few meters in diameter, the effective emissivity of the flame can be taken as one. Also, to be on the conservative side, the transmissivity is taken as one.

The inconsistency of the prediction of emissivity of flames and possible scale effects were treated in paper [3] presented for IFSHE8, Hefei, China, by Wighus, Brandt and Sesseng. Experience from large open fires have shown that similar temperatures have been measured as we have seen in the smaller, enclosed fires discussed in this paper. Further evidence of scale effects of enclosed fires is treated here. Some of these results have been publicly available for several years, but they have not been presented in international seminars or conferences.

## MODELLING OF HYDROCARBON FIRES OFFSHORE

Oil and gas were found in the North Sea and exploited in the years from 1970 onwards. The Norwegian Government initiated research activities to make the search and production of oil and gas both efficient and safe, and the Norwegian Fire Research Laboratory at SINTEF in Trondheim,

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Norway, was the central place for the research on fire safety. A large test facility was built, and a research project named "Modelling of Hydrocarbon Fires Offshore" was initiated [4] and run during 1984 - 89. The Norwegian oil companies took part in the research, and the development of computer models of the turbulent combustion of oil and gas was carried out at the SINTEF division Energy and Fluid Dynamics, section of Thermodynamics. The original objectives of the project were: "Development of tools for physical modelling and mathematical calculations to determine important parameters related to fire accidents offshore, such as burning time, flame lengths, heat loads and response to fire".

The work consisted of a series of model-scale experiments, simulating liquid pool fires in enclosures. Relatively small-scale experiments were carried out, the first in 1:10 scale of a module of an offshore platform, and the next in 1:4 scale. The 1:10 scale enclosure was 1 m x 2 m floor area, and 1 m high. The liquid pool at the centre of the floor was 0.5 m long and either 0.1 or 0.05 m wide.

The 1:4 scale enclosure was 2.42 m x 4.91 m floor area, 2.4 m high. The liquid pool at the centre of the floor was 1.25 m x 0.25 m.

Two types of fuel were used, SBP 62/82 and SBP140/165 (SPB: Special Boiling Point). The experiments were carried out with variation in air supply rate through a horizontal opening along one sidewall, at floor level. This made the change from fuel controlled, ventilation controlled and oxygen starved fire possible.

Tests were run with an empty enclosure, and with an array of small objects and a larger cylindrical object above the pool surface.

**Table 1. Key data for the experiments with empty enclosure [4]**

| Measured parameter | | 1:10-scale | 1:4-scale |
|---|---|---|---|
| Number of experiments | | 24 | 12 |
| Fire duration | [min:sec] | 8:30–32 | 20–60 |
| Ventilation rate | [kg/s] | 0.032–0.135 | 0.65–1.665 |
| Number of air changes | [$h^{-1}$] | 45–202 | 68–175 |
| | [kg/s] | 0.005–0.009 | 0.006–0.044 |
| Burning rate | [$kg/s{\cdot}m^2$] | 0.12–0.2 | 0.04–0.14 |
| | [mm/min] | 10.5–16.2 | 3.2–11.3 |
| Air to fuel ratio | [-] | 7–20 | 10–70 |
| Total heat release | [kW] | 200–380 | 280–2000 |
| Gas layer temperature (average) | [°C] | - | 170–650 |
| Ceiling temperature | [°C] | - | 180–800 |
| | CO [%] | 1.1–2.5 | 0–0.5 |
| Gas concentration | $CO_2$ [%] | 9.3–13 | 1.5–7 |
| | $O_2$ [%] | 0–1 | 10–19 |
| Mass fraction of fuel converted to soot | [%] | – | 7–15 |
| Incident heat flux | | | |
| -in front of the pool | [$kW/m^2$] | 27–39 | 7–30 |
| -behind the pool | [$kW/m^2$] | – | 40–78 |
| -absorbed by the pool surface | [$kW/m^2$] | 50–80 | 14–48 |
| Exit gas velocities | [m/s] | 7–9 | 2.8–9 |

Table 1 shows the variation of parameters and resulting effects in the two scales, with empty fire enclosures. The lack of values of gas layer and ceiling temperatures in the 1:10 scale experiments is due to limited number of thermocouples in this series. It is also to be mentioned that the tests were run for a relatively short time, and no equilibrium temperatures were obtained.

A scaling scheme based on empirical correlations was developed as a part of this project, by Jan P. Stensaas [5].

There is much evidence for how enclosed pool fires develop in the experimental results, but we will concentrate on gas temperatures and heat fluxes in this discussion. In the empty fire enclosure, the gas temperature above the pool and inside the enclosure were moderate, with a maximum average temperature of 650°C, and a ceiling temperature of 800°C. Heat fluxes in the order of 10-80 kW/m$^2$ in the vicinity of the pool were measured.

At the time of the project, the most accepted time-temperature curve for onshore buildings and industry was the ISO 834 [14] standard method for cellulosic material fires (A-class fires). British and Norwegian authorities had agreed upon the new standard time-temperature curve for laboratory test furnaces with the so-called Hydrocarbon Fire Curve, which later became ISO 834 – part 3 [6].

**Table 2. Key data for the experiments with objects above the pool inside the enclosure [4]**

| Measured parameter | | 1:10-scale | 1:4-scale |
|---|---|---|---|
| Number of experiments | | 2 | 8 |
| Fire duration | [min:sec] | 11–14 | 45–60 |
| Ventilation rate | [kg/s] | 0.08–0.1 | |
| Number of air changes | [h$^{-1}$] | 120–150 | 43–175 |
| Burning rate | [kg/s] | 9–12 | 19–30 |
| | [kg/s·m$^2$] | 0.18–0.24 | 0.06–0.095 |
| | [mm/min] | 14.5–19.4 | 4.85–7.7 |
| Air to fuel ratio | [-] | 7–11 | 16–80 |
| Total heat release | [kW] | 390–520 | 875–1300 |
| Gas layer temperature (average) | [°C] | – | 760–1000 |
| Ceiling temperature | [°C] | – | 370–1100 |
| Gas concentration | CO [%] | 2.3–2.7 | 0–0.7 |
| | $CO_2$ [%] | 9.3–9.4 | 2.5–12.8 |
| | $O_2$ [%] | 1–2 | 1.8–17.5 |
| Mass fraction of fuel converted to soot | [%] | – | 4–11 |
| Incident heat flux | | | |
| -in front of the pool | [kW/m$^2$] | – | 5–155 |
| -behind the pool | [kW/m$^2$] | – | 45–200 |
| -absorbed by the pool surface | [kW/m$^2$] | 70–90 | 20–32 |
| Exit gas velocities | [m/s] | 7.2–7.7 | 3–7 |

For the enclosure with objects above the pool, the measured temperatures were much higher, with a maximum average gas layer temperature of 1000°C, and a ceiling temperature of 1100°C. Heat fluxes of order of 200 kW/m$^2$ were measured in the vicinity of the pool. It is not clear why the objects influence the fire temperatures, but it may be either an increased turbulence in the combustion zone, or radiative properties picked up by the thermocouples inside the enclosure.

**Table 3. Average and maximum temperature measured in tests with objects inside the enclosure for test series in 1:4 scale [7]**

| Exp. Title | Run Date | Fuel supply temp. | $\Delta H_c$ | Average $Q_{fuel}$ | Max $Q_{fuel}$ | Average gas temp. | Max gas temp. | Max soot |
|---|---|---|---|---|---|---|---|---|
| | [YYMMDD] | [°C] | [kJ/g] | [kW] | [kW] | [°C] | [°C] | [g/s] |
| B1666-W3 | M880605 | 98 | 43.92 | 900 | 1089 | 282 | 935 | 2.6 |
| B1549-W1 | M880607 | 94 | 43.92 | 748 | 949 | 211 | 764 | 1.9 |
| B1474-L3 | M880908 | 97 | 43.92 | 1086 | 1540 | 380 | 969 | 2.9 |
| B1560-L1 | M880913 | 88 | 43.92 | 721 | 1785 | 269 | 880 | 2.3 |
| B1617-L1 | M880915 | 93 | 43.92 | 915 | 1211 | 307 | 943 | 3.4 |
| B1432-S2 | M880920 | 92 | 43.92 | 699 | 893 | 296 | 888 | 0.9 |
| C1398-S2 | M880926 | 50 | 44.80 | 733 | 1359 | 310 | 905 | 0.3 |
| C0410-S2 | M880928 | 47 | 44.80 | 660 | 1247 | 258 | 1264 | 2.0 |
| Min | | 47 | 43.92 | 660 | 893 | 211 | 764 | 0.3 |
| Max | | 98 | 44.80 | 1086 | 1785 | 658 | 1264 | 3.4 |

Table 3 from the enclosure tests in 1:4 scale sums up average and maximum temperatures measured in different experiments [7]. The nomenclature for the test name is B: Fuel type SBP 140/165, C: Fuel type SBP 62/82. The number in the middle is the air flow rate, and the last part represents the object configuration W: Water cooled, L: Large object, S: Small objects. The last number represents the location of the objects. Location 1: slightly downstream of the fuel pan, location 2: right above the fuel pan and location 3: between the fuel pan and the air inlet. The most special result in this case is C0410-S2, because the maximum temperature in this experiment reached 1264°C. This was a test with low ventilation rate, a grid of small pipes located right above the pool and the fuel with the lowest boiling point. The experimental log-book as seen in Table 4 tells about a special occurrence, not registered in any of the other tests.

**Table 4. Test log observations from test C0410-S2**

| Time mm:ss | Observation |
|---|---|
| 3:00 | The flames are penetrating the outlet opening |
| 5:30 | The flames are continuously exiting the outlet opening |
| ~20:00 | The gas interface layer is moving downwards to about 0.5 m above the floor level |
| 20:00 | The soot layer suddenly disappeared and was no more visible |
| END | The objects were significantly deformed. |

The temperatures and the heat flux density dropped a couple of minutes before the disappearance of the soot layer, from the maximum well above 1250°C and 200 kW/m$^2$. The soot concentration measured after the outlet opening dropped from 7% to 2 % in the same time interval.

The visual impression of the flames was described as "ghostly flames", and all the interior of the enclosure was clearly visible. This special occurrence may be influenced by soot formation and combustion, but this is not fully analysed and understood.

**Blast and fire engineering for topside structures**

In 1994, a Joint Industry Project, Blast and Fire Engineering for Topside Structures, was carried out, with partners from oil and gas companies operating in the North Sea. Large-scale tests were carried out both in UK and Norway, and interesting results were found in the Test Programme F3, Confined Jet and Pool Fires. This was carried out by RISE Fire Research (previously SINTEF NBL), in cooperation with Shell Research, Thornton UK [8] [9]. The dimensions of the test compartment were in most cases approximately 6 m high, 6 m wide and 12 m long (net. 415 $m^3$), with an opening of variable size at one short end. The fuels were in most cases condensate of crude oil from the North Sea, and vertical or horizontal spray fires with a release rate of 0.9 kg/s were tested. In some cases, liquid pool fires of 24 $m^2$ size were tested. The average over all tests of the maximum temperatures observed in each test was 1258 ± 80°C (N = 19). The maximum temperature measured in the tests was 1370°C, which is the maximum measuring range for the type K thermocouples used, indicating even higher temperatures during the period when the thermocouple measurements were peaking.

Heat fluxes measured in the 415 $m^3$ test compartment are shown in Table 5.

**Table 5. Enclosed fires – Results from experiments inside a 415 $m^3$ enclosure [8]**

| Fire type | Heat load |
|---|---|
| Jet fire hitting an object | Local heat loads of 350 – 400 kW/$m^2$. Typical heat loads to walls 200 kW/$m^2$. |
| Enclosed pool fire | A ventilation ratio of 0.8 of stoichiometric mixture gives the highest evaporation rate. Local heat load values of 300 – 350 kW/$m^2$ were measured in a room volume of 415 $m^3$ and a 24 $m^2$ condensate pool area. Typical heat load to walls 200 kW/$m^2$. |

A test of special interest in this programme is denoted JF9, with a jet of 0.95 kg/s liquid condensate pointing inwards into the compartment at a level of 1.5 m, centrally 3.6 m from the opening with dimensions 3.6 m x 2.9 m at one end wall. Cylindrical steel targets were located horizontally and vertically at the inner end wall. The vent opening was designed to give an air-to-fuel ratio close to 1 (stoichiometric mixture). In this test, thermocouples measured temperatures in the gas phase from the 0.5 m level up to the 4.5 m level above 1370°C, and the inner lining of the enclosure, made from stainless steel plates, melted or oxidized.

This test was repeated and showed severe fire development but, due to the destruction of the inner lining of the compartment in the first test, the repeated test was stopped earlier.

**Tunnel fires**

As mentioned in the presentation in Hefei [3], fires in tunnels have given temperatures with a maximum temperature of more than 1370°C. Tunnel fire tests were carried out in the Runehamar test tunnel in Norway [10]. The tests were conducted in a tunnel with a standard profile, with approximately 50 $m^2$ cross section area. The fuel was a setup with up to 720 pallets organized like a truck load. Most of the pallets were made from wood, a small amount was plastic. Again, the fire in an enclosure of a certain size, leads to temperatures well above 1200°C. An example of thermocouple temperatures from the Runehamar tunnel experiments is presented in Fig. 1.

The tunnel fire is also an enclosed fire, and the scale of the fires are large with up to 200 MW heat release rate.

**Jet fires**

Jet fire testing with a sonic jet of propane has been executed at RISE Fire Research since the 1980s [11]. This work has led to the development of a test standard for jet fire testing of passive fire protection [12]. Since that time, several hundred jet fires have been executed to test passive fire protection for documentation and certification purposes. Due to the request for jet fire testing with higher temperatures, an extended version of the standard jet fire test setup has been developed. It is based on the same propane jet setup as the standard jet fire test releasing a flow of 0.3 kg/s of evaporated propane gas through a 17.8 mm converging nozzle. The difference between the two different setups is that the high-temperature jet is released inside a more enclosed environment than the standard jet. Where the standard test setup consists of a jet released into an open box measuring 1.5 x 1.5 x 0.5 m, the high-temperature jet fire is placed inside an enclosure measuring approximately 3 x 3 x 3 m. The walls of the enclosure conserve more of the energy from the flame leading to higher temperatures inside the flame than what has been measured in the standard jet fire tests.

Temperatures have been measured inside small steel objects in the flame in both types of jet fire tests [13]. The relative distribution of all these measured temperatures is given in Fig. 2 for the standard jet fire and for the high-temperature jet fire tests with the extended enclosure. The graphs show the relative distribution of the temperatures measured in steps of 5°C. Of all measured temperatures, 1.5% from the standard jet fire test setup and 47% of the high-temperature jet fire test setup were above 1250°C. This shows that the increased enclosure size influences the heat load to a large extent. The tests are performed on several different types of passive fire protection applied to steel pipes, structural steelwork test specimens or other assembled configurations. There are variations between all tests, but the main configuration of the propane jet and the flow rate has been similar for all types of tests.

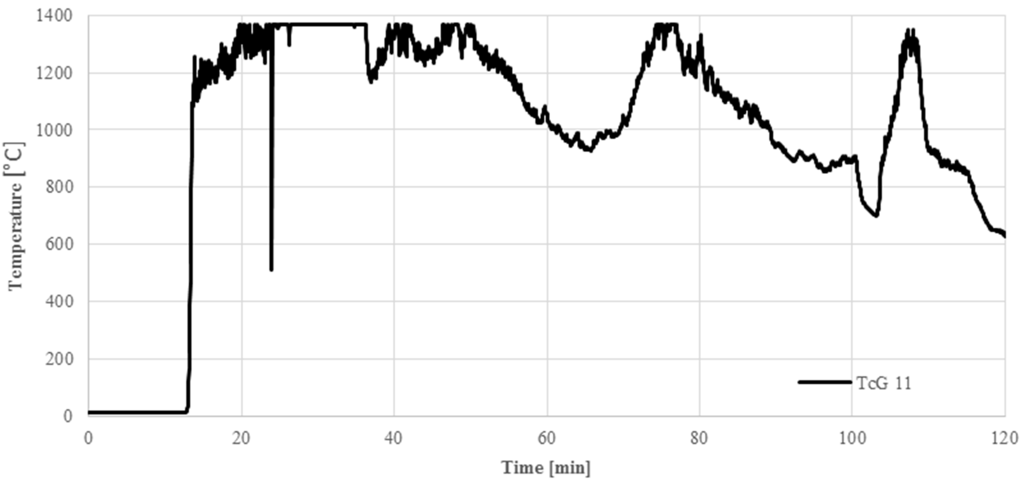


**Fig. 1.** Temperatures measured in the flame zone of a truckload of wooden pallets in a road tunnel [10].

The target temperature in the jet fire test with the extended enclosure is usually 1300°C, but in some tests, the temperature increases even further. This is particularly the case in tests where there are several test objects inside the flame. Most of the temperature measurements are made with type K thermocouples that cannot measure above 1370°C. The software rejects measurements for K type thermocouples above this value. The measurements recorded when the type K thermocouples are peaking are substituted with 1370°C in this data set. These measurements can be shown as a distinct peak in the graph. The real values of these temperatures are probably distributed further above 1370°C. In some of the tests, the type K thermocouples are supplemented with platinum type R thermocouples that can measure temperatures up to 1760°C to capture the highest temperatures. As seen in Fig. 2, there is a small number of temperatures measured above 1370°C with R type thermocouples. A total of 1.5% of the measurements are 1370°C or above. The highest single measurement in this data set is 1520°C.

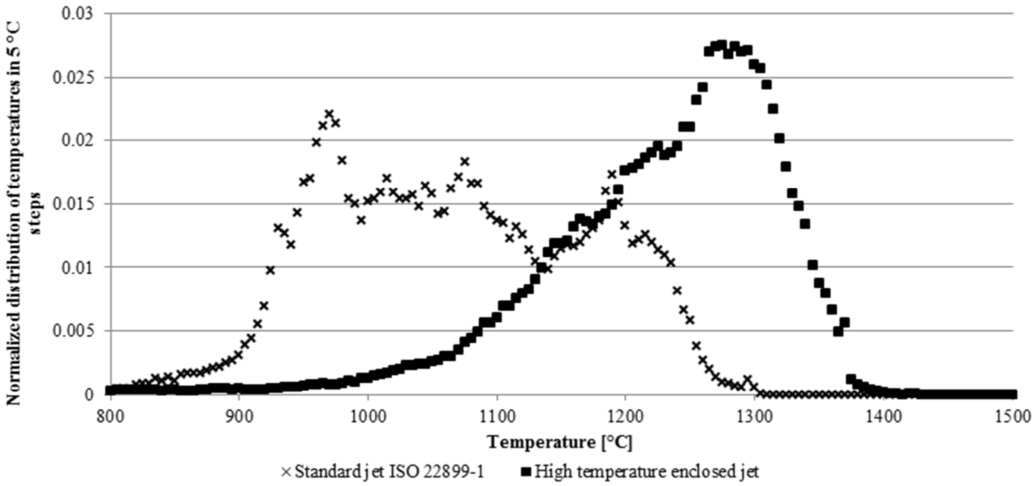


**Fig. 2**. Normalized distribution of all individual single measured temperatures from 20 standard jet fire tests (N=353 292) and 55 high-temperature jet fire tests (N = 934 286). The average number of measurement positions for each test is 6.2. N is the total number of measurements made, from each of the measurement positions every second during the tests.

## DISCUSSION

Based on experience from a variety of enclosed fires, we can conclude on some typical features of these fires:

- The heat loss from the fire zone will normally be less than in open fires.
- The enclosure traps radiation and the enclosure walls, ceiling and floor get hot. Insulated walls will increase the radiation trapping in the enclosure.
- Re-radiation from the enclosure increases the combustion efficiency due to higher flame zone temperature.
- Conditions close to stoichiometric or in slightly under-ventilated fires in enclosures lead to highest temperatures and heat fluxes.
- Objects, piping and surrounding walls, ceiling and floor absorb heat, but will re-radiate when hot.
- Surfaces of insulated objects re-radiate more than uninsulated objects and make the fire environment hotter.
- Congestion seems to increase the temperature in enclosures in some cases. Turbulence may be the key factor. However, no direct experimental evidence of the mechanisms for this is available.
- A large, thermally thick flame will have similar effects on the fire temperature as an insulated enclosure wall.

### Outliers or indications of typical effects

In experimental work one will now and then register effects that are not easily repeated, like some of the examples we have shown above. Ideally one should have made more repetitions and searched for the reasons for the extremes that are registered, but in large-scale fire experiments the cost of each experiment limits the amount of repetitions particularly for tests that reach very high temperatures and damage the test setup. The results from the high-temperature jet fire tests are repeated several times even though the target temperatures for these tests are usually around 1300°C. However, in the presented tests, no lack of measurements or malfunctioning equipment has been in use to explain the extremes that were registered, so one should not disregard these evidences of the high temperatures measured, nor the high heat fluxes. The question which should be discussed further is if these results are due to more efficient mixing of reactants, if the radiation trapping inside the enclosure is the most important, or if it is a scale effect, as indicated in the presentation in Hefei [3].

**Summary of the fire experiments that have reached higher temperatures than expected**

- The fires in the 2 $m^3$ enclosure (1:10 scale) never reached temperatures exceeding the HC-curve. However, these experiments were not run to steady-state conditions.
- Most of the experiments in the 12 $m^3$ enclosure (1:4 scale) reached high temperatures, but within 1100°C, which is in line with the HC-curve. However, one test, with small objects placed above the pool fire, placed in the upstream position for the air supply, gave higher temperatures than the HC-curve.
- Most of the experiments in the 415 $m^3$ enclosure passed the highest temperature of the HC-curve within a short time after ignition. One extreme test, JF9, with a horizontal spray fire of condensate into the enclosure, with an opening at one end wall designed to give approximately stoichiometric air/fuel conditions, gave temperatures much above the HC-curve, even above the measurement range of typical thermocouples used in fire research (above 1370°C).
- Tunnel fires with wood pallets as fuel also gave similar temperatures much above the HC-curve, even above the measurement range of typical thermocouples used in fire research (above 1370°C).
- Enclosed jet fires reach higher temperatures than open jet fires. The presence of the enclosure clearly increases the majority of the measured temperatures inside the jet flame.
- Even though the intended temperature in the jet fire test is 1300°C, temperature measurements above 1370°C are not uncommon.
- Objects inside the flame may increase the turbulence and the measured temperatures.

**Consequences for time-temperature curves**

Figure 3 shows three existing time-temperature curves which are in current use. The two ISO-curves are familiar to most of the fire safety community, but the third, denoted RWS-curve, is specifically developed to represent catastrophic tunnel fires. It was developed in Europe and is named after the Dutch Rijkswaterstaat, the authorities for infrastructure and water management in the Netherlands. Its background is full-scale tests with a burning truck-load of wooden and plastic pallets inside a typical road tunnel [10]. The time-temperature curve mimics a fast-growing fire reaching 1200°C within less than 10 minutes, growing gradually to a maximum of 1370°C at 60 minutes, and then diminishing gradually until 120 minutes. The interesting point is that this experiment-based time temperature curve is much more severe to constructions and tunnel lining than what is used in the offshore and process industry.

## CONCLUSIONS

From experiments with hydrocarbon fires, both pool fires, liquid spray fires and gaseous jet fires, temperatures well above the HC-curve are experienced. In special situations, temperatures are so high that conventional thermocouples (Type K, Chromel-Alumel) are not recommended for use. We have shown that these high temperatures occur in enclosed fires, at different scales.

At least three factors influence the temperature development in a fire: Stoichiometry and mixture, congestion leading to increased turbulence and scale (size of flame or compartment). For compartment fires this is not fully understood and documented.

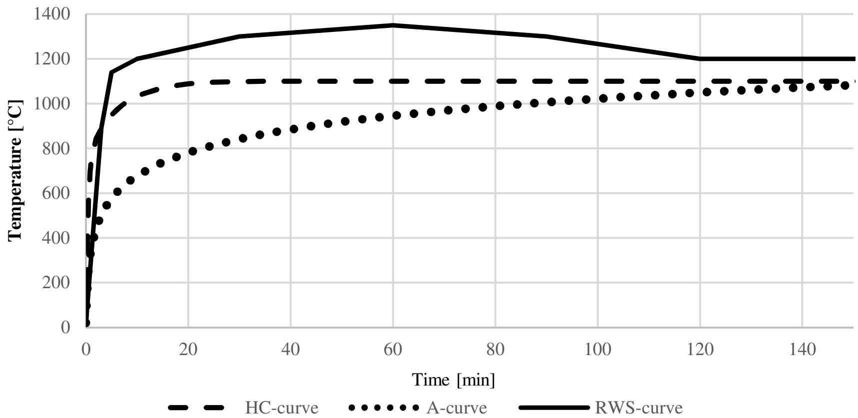


**Fig. 3.** Three existing time-temperature curves used for fire testing.

The standard time-temperature curves described in ISO 834 have the purpose to reproduce one fire situation which is used to qualify constructions elements, for comparison. However, these curves are often used as an input to fire hazard assessment. Experiments with enclosed fires as described in this paper has shown that, in some cases, the temperatures measured inside the fire reach very high values. Most of the temperatures in fire experiments are measured using type K thermocouples. These cannot measure above 1370°C and may give a false impression that this is an upper limit for temperatures in fires. Platinum type R thermocouples can measure higher temperatures and are used in some high-temperature jet fire tests. They show that the temperatures in the jet fire enclosure increase above 1370°C up to the highest measured temperature of 1520°C in one of the tests.

These enclosed fire experiments show that even relatively small fires can reach very high temperatures under certain conditions. The experiments studied here were not planned or executed to study this phenomenon. This means that the available data set is not optimal to investigate exactly what causes these temperatures to reach higher than expected in some cases. An evaluation of the available measurements and observations from these extraordinarily hot fire tests indicates that congestion and turbulence generating objects is one of the important parameters that may increase the efficiency of the combustion and increase the temperature. Other important parameters are the fuel to air ratio and how the soot particles interact with the flame plume. Finally, the enclosure volume compared to the heat release rate of the fire, insulation and the ventilation properties of the enclosure are important.

The experiments presented in this paper also focus on what have been "outliers" in the test series, where repeated experiments have not shown similar performance. The extremes seen in such experiments should not be disregarded but should be further investigated to find the causes. There are clear indications that this is a scale effect of flames that is enhanced by the walls of the enclosure.

A review of the relevance of the design principles, the engineering standards and the relevance of the calculation tools should be carried out, with the aim to update them based on state-of-the-art knowledge.

There is a need for a project to revisit the time-temperature curves and test set-up for standard fire tests, both in furnaces and in jet fire testing. Focus should be on the conditions under which the higher temperatures occur, with a systematic investigation of which factors among enclosure size and geometry, wall properties, obstructions and ventilation conditions that govern the temperature development. The outcome of this project should be a better design basis for offshore and land-based process industry, to avoid designs that promote the occurrence of high temperatures and heat fluxes.

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