Thermal Test Requirements and Their Verification by Different Test Methods

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Abstract

This paper describes a new propane - fired test facility and the results of tests with a big vessel calorimeter to demonstrate compliance with the IAEA thermal test requirements.

Introduction

The thermal test requirements for Type B-packages in § 628 of the IAEA regulations (safety series No. 6) are based on a liquid hydrocarbon pool fire. Using this thermal test, a lot of test conditions to provide a sufficient fire engulfment have to be met. But also any other thermal test which provides the equivalent total heat input to the package shall be used.

The total heat input is

$$Q = q \cdot A \cdot t \qquad (1)$$

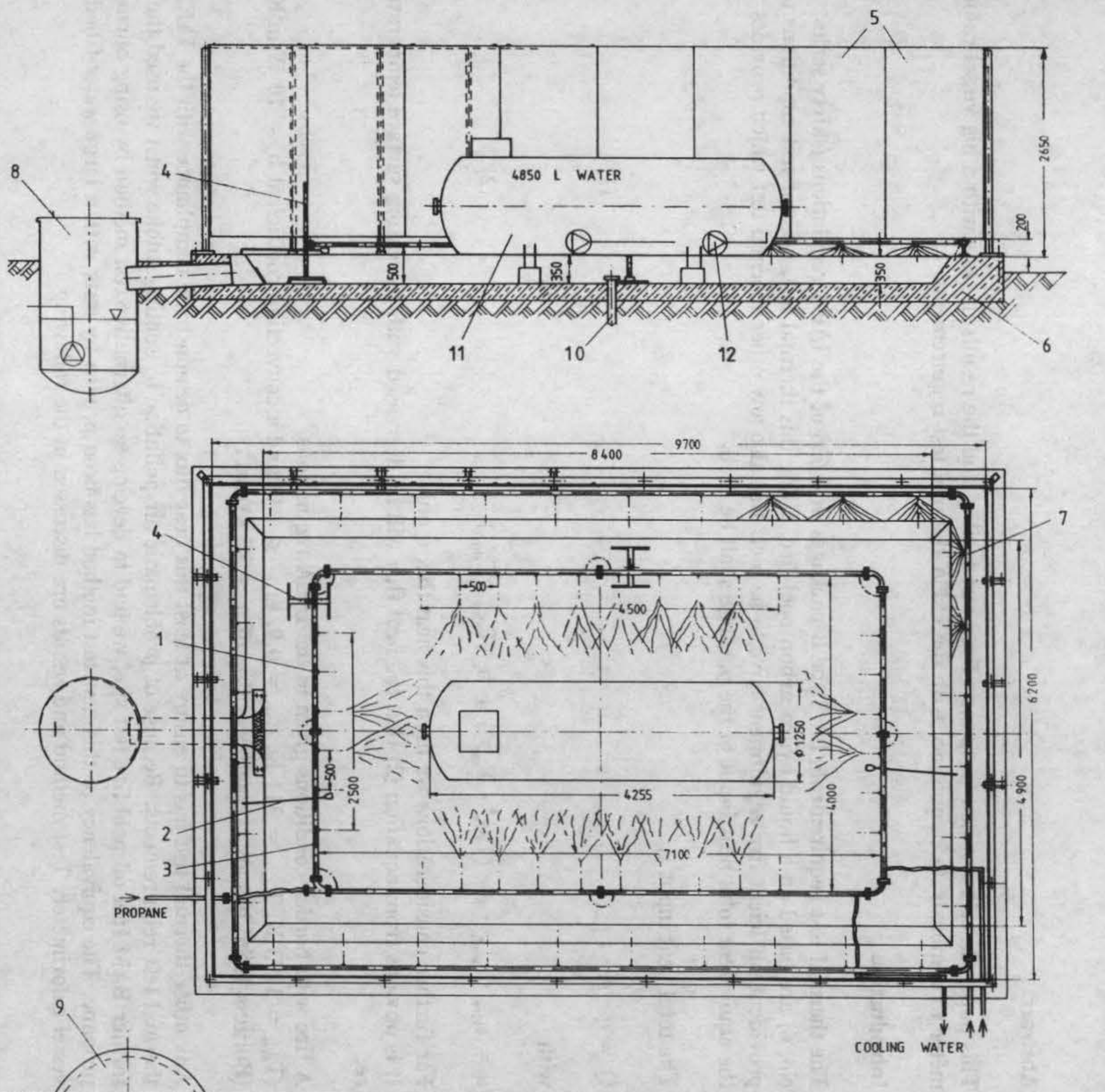
with

$$q = \epsilon_{Fire} \cdot \epsilon_{surf.} \cdot \sigma \cdot (T_{Fire}^4 - T_{surf.}^4) + h_c\,(T_{Fire} - T_{surf.}) \qquad (2)$$

For further considerations we need this heat flux q only.
It is obvious from equation (2) that the heat flux will be decreased with increasing surface temperature.

A fire with border conditions given in the IAEA regulations ($T_{Fire} = 1073$ K, $T_{surf.} = 311$ K, $\epsilon_{Fire} = 0.9$, $\epsilon_{surf.} \leq 1.0$) and a convection coefficient $h_c = 10$ W/m²K (Burgess 1986) has an average heat flux of $q \leq 75$ kW/m².

Any other thermal test has to ensure at least this heat flux to demonstrate compliance with the IAEA thermal test requirements. Because of problematic air pollution by sooting smoke when we used the former BAM fuel oil pool fire test site, we had to develop an alternative test method by using burning propane. The equivalency of this new test method has been proven by tests with a large water-filled vessel calorimeter. Test method and results are discussed in the following.



Pos. No.	Component	Amount
1	Gas Release Nozzle (ϕ 1,5 mm)	20
2	Igniting Burner	2
3	Gas Pipe (double walled)	1
4	Gas Pipe Support	6
5	Wind Protection Wall Sheet	28
6	Concrete Trough	1
7	Trough Cooling Water Pipe	1
8	Pump Sump	1
9	Gas Installation Sump	1
10	Underground Pipe (Not used in these tests)	1
11	4850 l Pressure Vessel (DIN 4680)	1
12	Immersion Pump (10 000 l/h)	2

BAM

Propane - Fired Test Facility

Description of the New BAM's Propane-Fired Test Facility

The test object is located inside a flat concrete trough. The fire engulfment is produced by burning propane which is released in liquid state from nozzles in a pipe that surrounds the test object. The propane is stored in two earth-mounded tanks (17 m^3 and 12 m^3) positioned 100 m away, and carried by a pump station through an underground pipe to the burner ring pipe. The burner ring pipe (for these tests equipped with 20 nozzles of 1.5 mm diameter; 7 at the long, 3 at the short sides each) is double walled and water cooled. To prevent destruction, the concrete surface also is cooled by water sprayed on from a water pipe ring. To eliminate wind effects the concrete trough is surrounded by a wall made of steel sheets. The exact dimensions and positions of the fire test facility components are shown in Figure 1. The fire test method had been developed for and used in several tests on LPG tanks to investigate different kinds of fire protection measures (Schoen et al. 1989, Droste 1992).

Vessel Calorimeter and Instrumentation

The heat flux is dominated by the radiant heat exchange (first term in (2)), and strongly depends on environmental effects (wind, soot) and on the size of the test object (Burgess and Fry 1990, Keltner und Moya 1989). A large package is a significant "heat sink" for a fire and will drop the average fire temperature if the flame geometry and/or the test conditions are not properly designed. Thus a fire calibration specimen to compare different thermal test methods must have the following properties to create conservative open fire test conditions: a large surface and a big heat capacity in combination with a good heat conduction. For our tests we used a pressure vessel (cylindrical part with a length of 3.6 m, two Korbbogen-type heads, total length of the vessel 4.25 m; tank material mild steel, wall thickness 6.5 mm) filled to 100 % with 4850 l water.

Two immersion pumps on the bottom line inside the vessel produced a strong enforced convection to get immediately a temperature equilibrium inside the liquid contents. The vessel surface to be used for the heat flux calculation is 17.5 m^2. It is noteworthy that the heat capacity of such a calorimeter is equivalent to a steel cask with a mass of about 43,000 kg.
Figure 2 shows the plan of the thermocouple (tc) positions. Water temperatures have been measured at 3 cross-shaped arrays (9 tc each) and additionally in the axis line (tc 210-213). Tc-No. 214-217 measured wall temperatures. Tc No. 300-316 measured fire temperatures in a distance of 100 mm to the vessel surface, with exemption of No. 304 and 314 which had a distance of 200 mm. All thermocouples were NiCr/Ni (Heraeus, MT-Ta-1 CA/32/15) covered with stainless steel, outer diameter 3.2 mm (fire temperatures) or 1.5 mm (inside vessel temperatures). To "smooth" the fire temperature values, we put steel cones (20 mm length, 15 mm diameter, bore hole 3.2 mm) onto the tips of the fire thermocouples; from furnace tests we know that this decreases the temperature measured by 20 to 30 °C compared to values measured with "open" thermocouple tips.
Figure 3 shows the vessel inside the fire test facility before and Figure 4 during a fire test.

Test parameters

We ran a series of nine tests with a variation of the propane consumption and - to some extent - of the vessel height above ground. Each test had only been run over a time that caused a water temperature increase of nearly 30 °C. The test parameters and the average heat flux values calculated from the linearized water temperature increase during a test are shown in table 1.

Although we have observed clear and smokeless flames, the surface of the test vessel was immediately covered with soot; we assume that $\epsilon_{surface}$ was around 0.95.

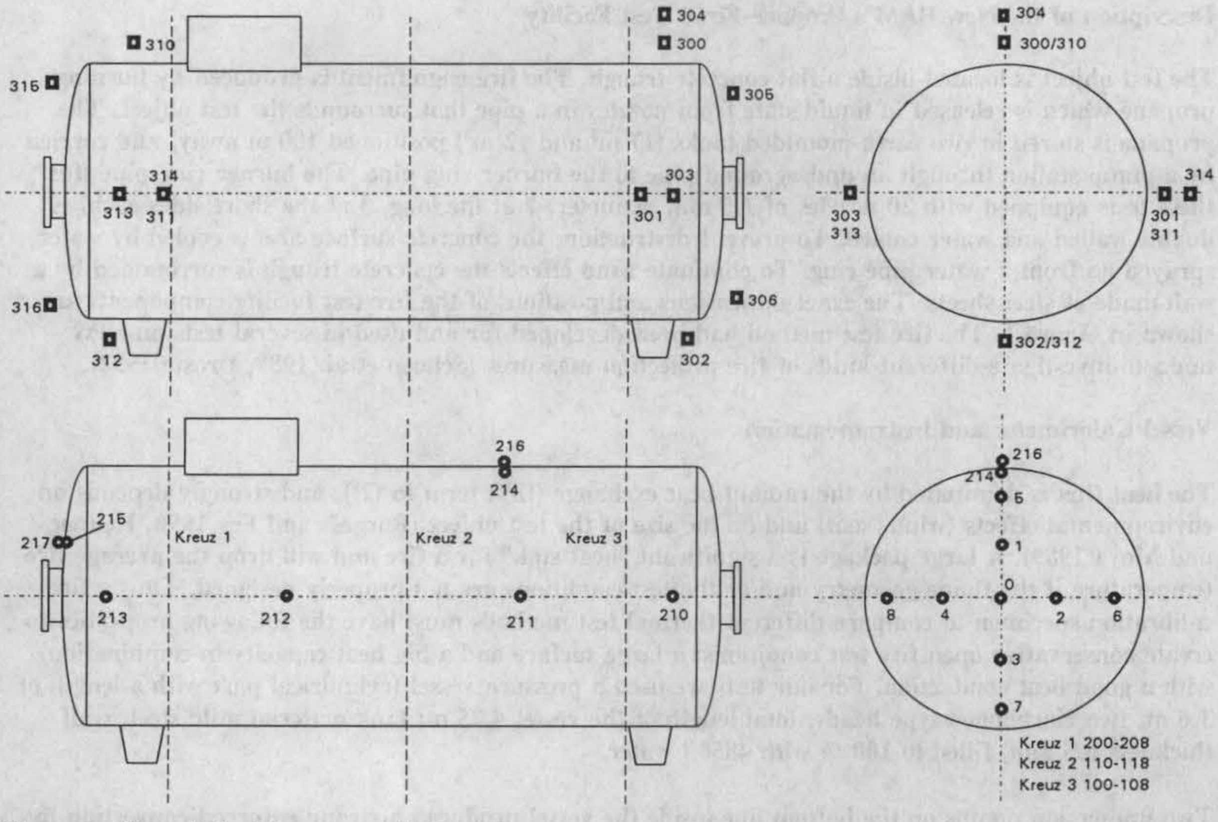


Figure 2: Plan of the Thermocouple Locations

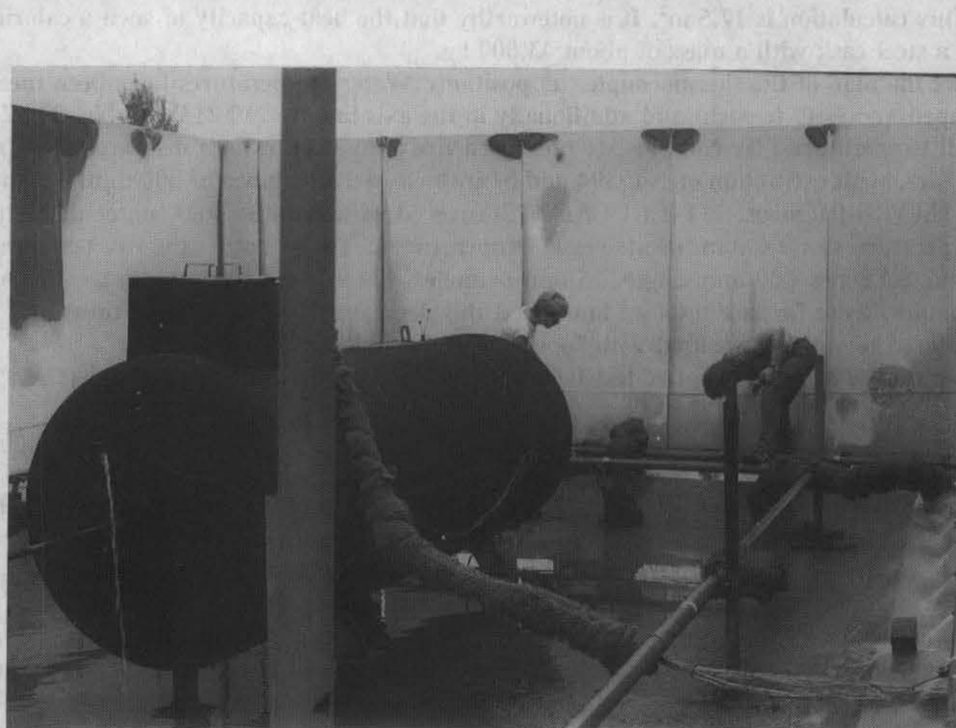


Figure 3: Vessel Calorimeter

Figure 4:
Vessel in
a Fire Test

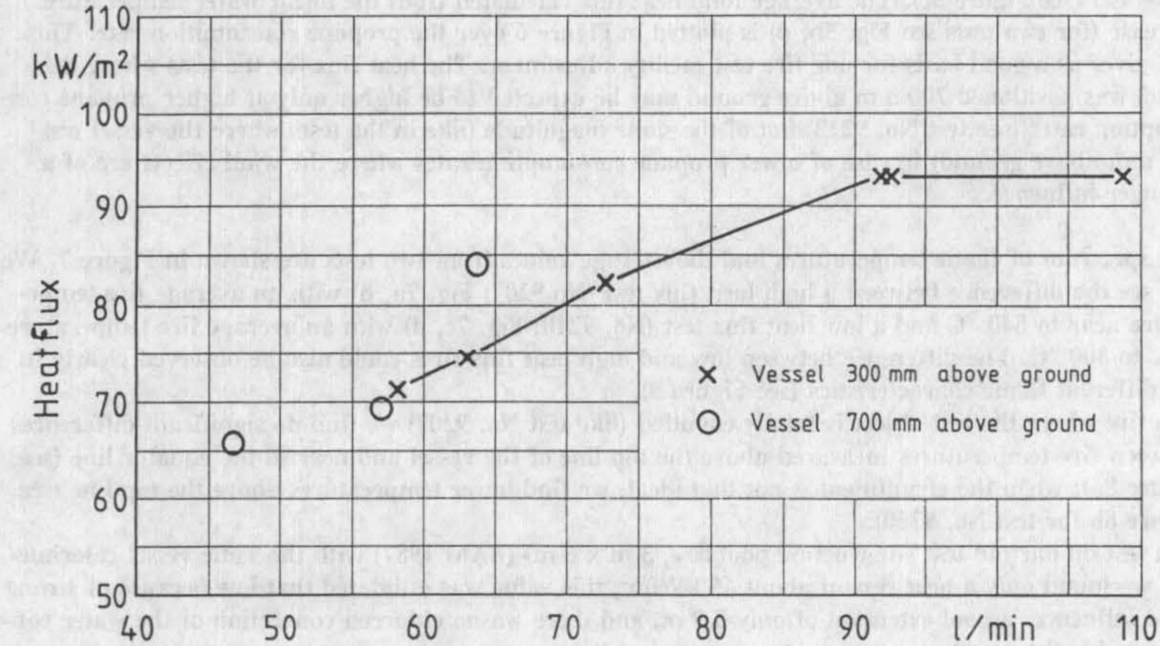


Figure 6: Total Average Heat Flux over Propane Consumption Rate

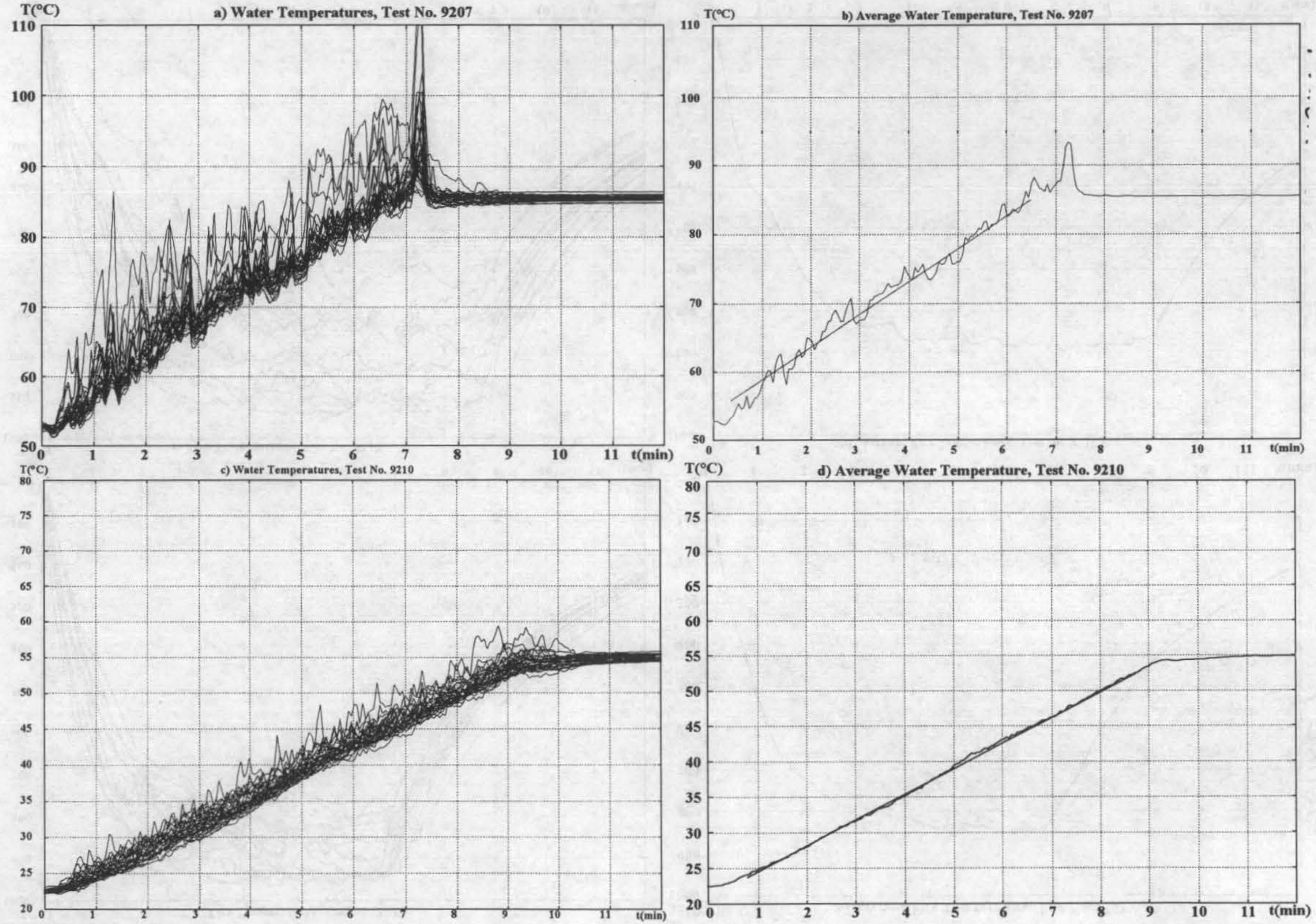
Table 1: Test Conditions

TestNo.	Propane Consumption in l/min	Vessel Bottom Line Above Ground in mm	AverageTotalHeatFlux in kW/m^2
9206	92.40	350	93
9207	92.14	350	93
9208	72.80	350	82
9209	108.80	350	93
9210	58.11	350	71
9211	63.00	350	75
9212	63.75	700	84
9213	46.80	700	66
9214	57.00	700	69

Test Results

Results of water temperature measurements are shown for two tests in Fig. 5. During the first two tests we noticed strong fluctuations of the thermocouple signals (Fig. 5a), nevertheless we could estimate the linear temperature increase very well. With a better vessel earthing and with insulation of the thermocouple lines crossing the fire we could eliminate this effect and registered a smooth temperature increase. The good convection inside the vessel caused consistency of all values measured inside the vessel (see Figure 5c). The average total heat flux calculated from the linear water temperature increase (for two tests see Fig. 5b, d) is plotted in Figure 6 over the propane consumption rate. This plot gives us a good basis for our fire test facility adjustment. The heat flux for the tests where the vessel was positioned 700 mm above ground may be expected to be higher only at higher propane consumption rates (see test No. 9212) but of the same magnitude (like in the tests where the vessel was 350 mm above ground) in case of lower propane consumption rates where the wind effects are of a stronger influence.

The spectrum of flame temperatures and the average values from two tests are shown in Figure 7. We can see the difference between a high heat flux test (No 9207; Fig. 7a, b) with an average fire temperature near to 840 °C and a low heat flux test (No. 9210; Fig. 7c, d) with an average fire temperature near to 800 °C. The difference between low and high heat flux fires could also be observed clearly in the different flame characteristics (see Figure 9).
In a fire where the test object is totally engulfed (like test No. 9207) we find no significant differences between fire temperatures measured above the top line of the vessel and near to the equator line (see Figure 8a); when the engulfment is not that ideal, we find lower temperatures above the top line (see Figure 8b for test No. 9210).
In a test on our old test site (fuel oil pool fire, 3 m x 6 m) (BAM 1987) with the same vessel calorimeter, we found only a heat flux of about 45 kW/m^2; this value was estimated that low because of strong wind influence, a pool extension of only 0.9 m, and there wasno enforced convection of the water contents inside the vessel.



a) Water Temperatures, Test No. 9207
b) Average Water Temperature, Test No. 9207
c) Water Temperatures, Test No. 9210
d) Average Water Temperature, Test No. 9210
T(°C)
t(min)

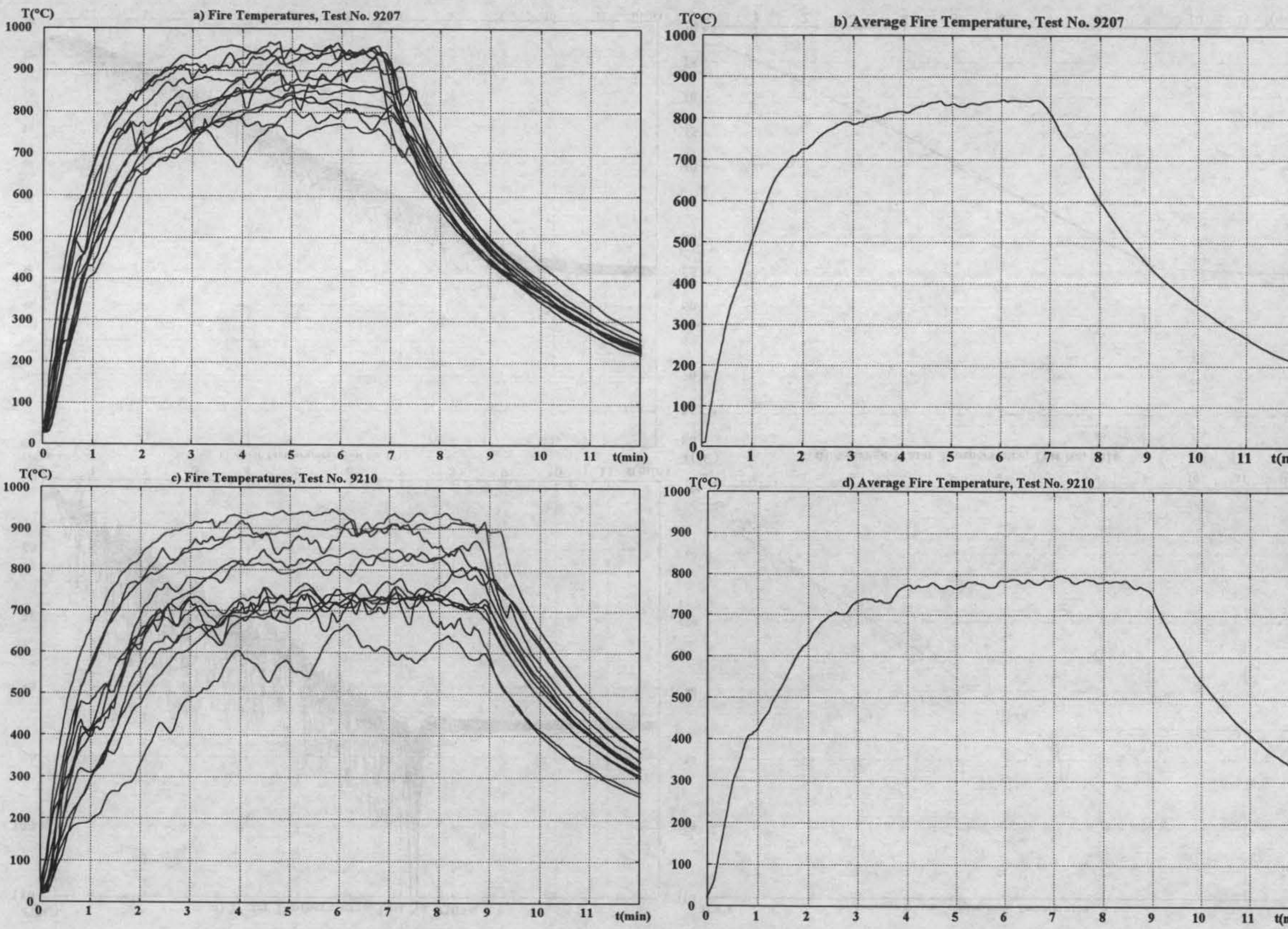

a) Fire Temperatures, Test No. 9207
b) Average Fire Temperature, Test No. 9207
c) Fire Temperatures, Test No. 9210
d) Average Fire Temperature, Test No. 9210
T(°C)
t(min)

FIGURE 7

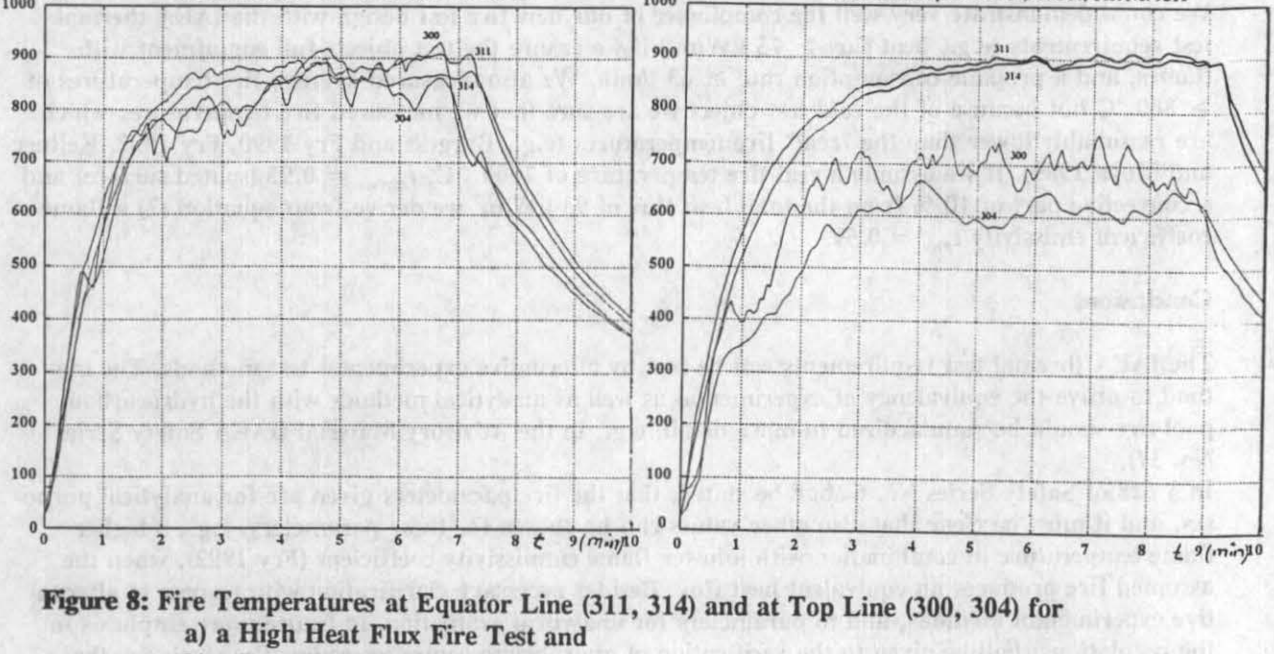


Figure 8: Fire Temperatures at Equator Line (311, 314) and at Top Line (300, 304) for
a) a High Heat Flux Fire Test and
b) a Low Heat Flux Fire Test

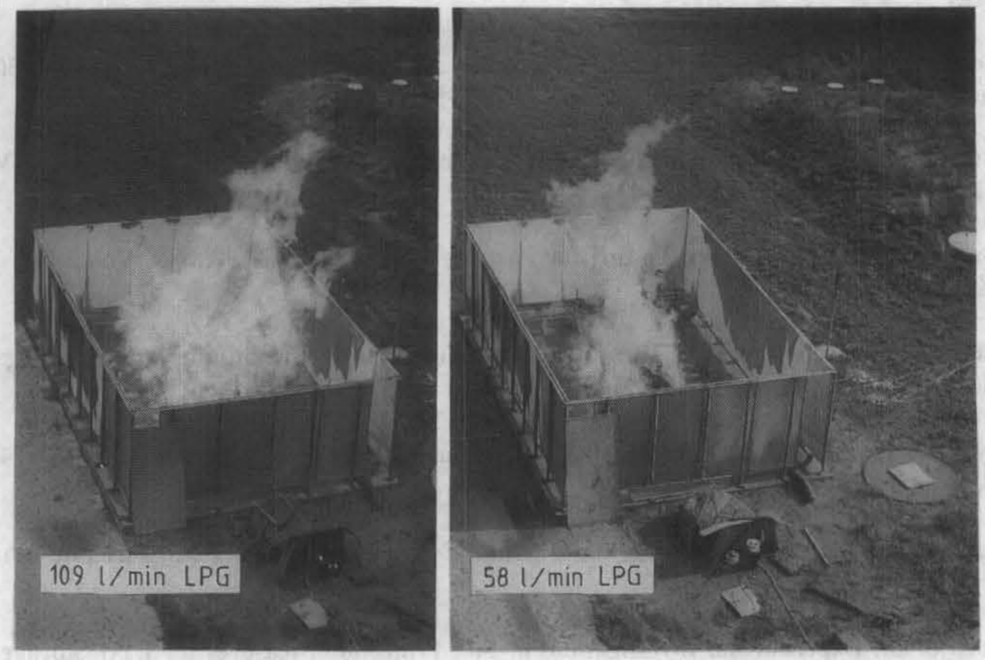


Figure 9: Flame Characteristic of a High Heat Flux (Left) and a Low Heat Flux (Right) Fire Test

Discussion of the Test Results

We could demonstrate very well the compliance of our new fire test design with the IAEA thermal test requirements (e.g., heat flux ≥ 75 kW/m^2) if we ensure the test objects full engulfment with flames, and a propane consumption rate ≥ 63 l/min. We also measured average fire temperatures of ≥ 800 °C but because of the cold test object we are sure that we measured fire temperatures which are reasonably lower than the "real" fire temperatures (e.g., Burgess and Fry 1990, Fry 1992, Keltner and Moya 1989). If we assume a real fire temperature of 1000 °C, $\epsilon_{surface} = 0.95$ (sooted surface) and a convective part of 10 % from the total heat flux of 93 kW/m^2 we derive from equation (2) a flame coefficient emissivity $\epsilon_{Fire} = 0.59$.

Conclusions

The IAEA thermal test requirements can be met by alternative experimental test methods. The method to prove the equivalency of experimental as well as analytical methods with the hydrocarbon pool fire should be standardized in more detail, e.g., in the Advisory Material (IAEA Safety Series No. 37).
In § 628 of Safety Series No. 6 shall be stated, that the fire parameters given are for analytical purposes, and it must be clear that also other values can be chosen for these parameters, e.g., a higher flame temperature in combination with a lower flame emmissivity coefficient (Fry 1992), when the assumed fire produces an equivalent heat flux. Besides necessary clarification with respect to alternative experimental methods, and to parameters for analytical evaluation, in future more emphasis in the regulations shall be given to the verification of appropriate computer codes. Proposals for the IAEA revision process will be made by Germany.

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