Proceedings of the 19th International Symposium on the
Packaging and Transportation of Radioactive Materials
PATRAM 2019
August 4-9, 2019, New Orleans, LA, USA

Fire reference test for IAEA package thermal testing in a propane gas fire test facility

Martin Feldkamp **Thomas Quercetti** **Frank Wille**

Bundesanstalt für Materialforschung und -prüfung (BAM)
Unter den Eichen 87
12205 Berlin, Germany

Abstract

Packages for the transport of radioactive material shall withstand severe accidents. Therefore, the IAEA Regulations define different test scenarios to cover severe hypothetical accident conditions. One of these tests defined in detail is the thermal test, mainly consisting of a 30 minute fully engulfing 800 °C pool fire or an equally severe fire test. The heat fluxes into the package are of significant importance and depend substantially on the fire characteristics and the surface temperature of the package.

In order to investigate the heat fluxes over a wide range of surface temperatures during a propane gas fire test and to get information about local fire impact a fire reference package, representing the outer geometry of a specific type of transport cask for radioactive waste, was designed. A closed steel sheet cylinder with a wall thickness of 10 mm was chosen as fire reference package. The cylinder was filled with refractory insulation material and instrumented with thermocouples distributed all over the cylinder. The local steel sheet temperatures measured allow the determination of local as well as global heat fluxes as a function of time and surface temperature.

With this fire reference package three open-air propane gas fire tests were performed at BAM's open air fire test stand. The flame exposure time period was changed for the different fire tests. Furthermore, the wind conditions changed between and during the tests. Test stand parameters like wind shield location and propane gas volume flow were chosen constant for the three tests. The test results were used to determine the changes of heat flux into the fire reference package in relation to the package surface temperature. This data also allows the calculation of local characteristics of the propane gas fire as there are the flame temperature, the fire convection coefficient and the radiation exchange coefficient in a first approach. The recently conducted tests provide an initial picture of local fire characteristics of the propane gas fire test facility. The test shows that the propane gas fire covers the IAEA-fire over a wide range of surface temperatures with the chosen test stand parameters.

Introduction

Packages for the transport of radioactive material shall withstand severe accidents. Therefore, the IAEA Regulations for the Safe Transport of Radioactive Material [1] define different test scenarios to cover severe hypothetical accident conditions. One of these tests is the thermal test, mainly consisting of a 30 minute fully engulfing 800 °C pool fire or an equally severe fire test. The heat fluxes into the package are important and depend substantially on the fire characteristics and the surface temperature of the package. The thermal environment during the fire test is defined in detail in the IAEA Regulations [1] and its Advisory Material [2]. The Advisory Material [2] states that certain fire parameters are specified which are essential input data for the calculation method but are generally uncontrollable parameters in practical tests. Standardization of the practical test is therefore achieved by defining the fuel and test geometry for a pool fire and requiring other practical methods to provide the same or greater heat input. In [2] further literature with different test methods to verify the required heat input and methods to prove the thermal environment is presented. In [3] several measurement techniques are discussed, as the slug calorimeter operating with temperature change measurements. This nonlinear inverse heat conduction was also described in [4] and used for the calorimetric tests in [5]. In [6] it was shown that a propane gas fire can meet the requirements of the IAEA Regulations [1] with a heat flux higher than 75 kW/m² at low surface temperatures. At higher surface temperatures the heat flux into the specimen decreases. With the fire characteristics given in [1], and [2], namely the convection coefficient, the flame temperature, the emissivity of the package surface, and the emissivity of the fire, a heat flux into the package in dependence of its surface temperature is defined for numerical calculations. This heat flux curve, resulting from these fire characteristics, will be discussed as ‘IAEA-curve’ and described more precisely. The ‘IAEA-curve’ will be used for comparisons with the, over a wide range of surface temperatures measured, heat flow rates in a propane gas fire of the fire test facility at ‘BAM Test Site Technical Safety’ described in [7].

Therefore, a fire reference package was designed. A similar package for calorimetric tests performed in a circular pool fire is shown in [5]. The fire reference package designed consists of a closed steel sheet cylinder with a length of 1,500 mm, an exterior diameter of 1,050 mm, and a wall thickness of 10 mm. The cylinder was filled with refractory insulation material and instrumented with thermocouples distributed all over the cylinder. The measured local steel sheet temperatures allow the determination of local as well as overall integral heat fluxes versus time and versus surface temperature.

With this fire reference package three open-air propane gas fire tests were performed. The flame exposure period was changed for the different fire tests. Furthermore, the wind conditions changed between, and during the tests. Test stand parameters, like wind shield location, and propane gas volume flow, were chosen constant for the three tests.

The calculation of heat fluxes and fire characteristics is proposed and conducted with the data of one of the performed fire tests. The overall average fire characteristics calculated in this approach gives physically plausible results as an effective flame temperature of $\mathrm{T_f} = 833.1\,^{\circ}\mathrm{C}$, a radiation exchange coefficient of $\varepsilon_{\mathrm{e}} = 0.63$ and a convection coefficient of $\alpha = 66.2\,\frac{\mathrm{W}}{\mathrm{m^2K}}$. The presented test provides in addition a picture of averaged local fire characteristics of the propane gas fire. The test shows that the propane gas fire covers the IAEA-fire for numerical calculations over a wide range of surface temperatures with the chosen test stand parameters.

Fire Reference package

The fire reference package, representing the outer geometry of a specific type of transport cask for radioactive materials, was built as a closed hollow steel cylinder with a length of 1,500 mm and a diameter of 1,050 mm. The wall thickness was entirely 10 mm. The photo in Figure 1 shows the reference package during manufacturing. The cylinder jacket is made of rolled steel sheet and lengthwise welded. The ends were closed by welded lids. The mass was 522.5 kg, and the outer surface 6.68 m². The cylinder cavity was filled with refractory insulation material in order to suppress any convection process inside. The material had an application temperature up to 660 °C and a fiber melting point of more than 1000 °C. The entire outer surface of the cylinder was treated with black baked enamel finish in order to have an emission coefficient of the surface close to the value of 1. The heat resistance of the finish was up to a temperature of 1200 °C, high enough to withstand the propane gas flame temperatures of the fire.

FIGURE 1. Manufacturing of the cylindrical reference package and filling of the cavity with insulation material after instrumentation with thermocouples.

The measurement of the package temperatures during the fire test was solved by installing thermocouples at the surface of the inner and outer walls (Figure 3, left). In order to measure mostly the real wall temperature, 2 mm deep blind holes were drilled into the wall where the measuring end of a thermocouple was inserted using heat sink compound for optimized heat transfer (Figure 3, right). The thermocouple was bended at the end and fixed by spot welded wire to the steel surface. We used calibrated Ni-CrNi-thermocouples from type K with a length of 15 m and a diameter of 1.5 mm. The inner installed thermocouples leave the reference package as a bundle through a hole at the downside and protected by mineral wool on the short way from the package through the fire to the bottom of the fire test facility which is filled with water.

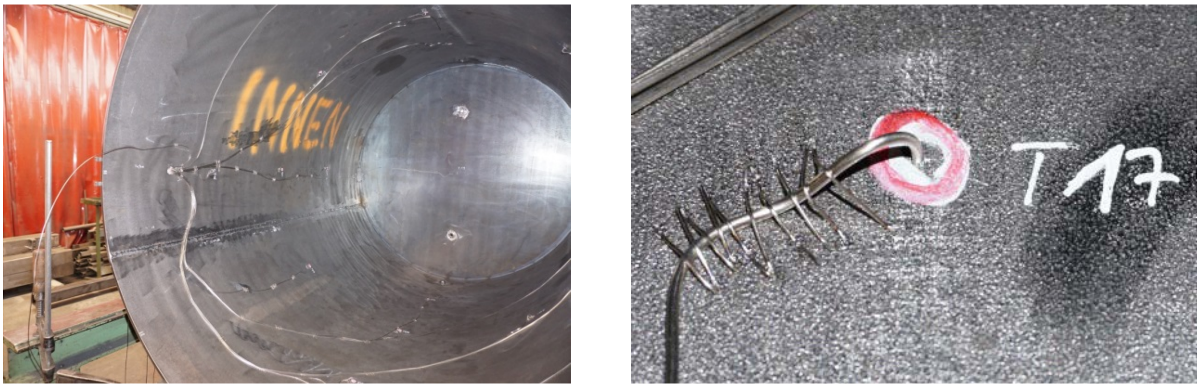


FIGURE 2. Thermocouples at the surface of the inner wall and detail of a thermocouple installation.

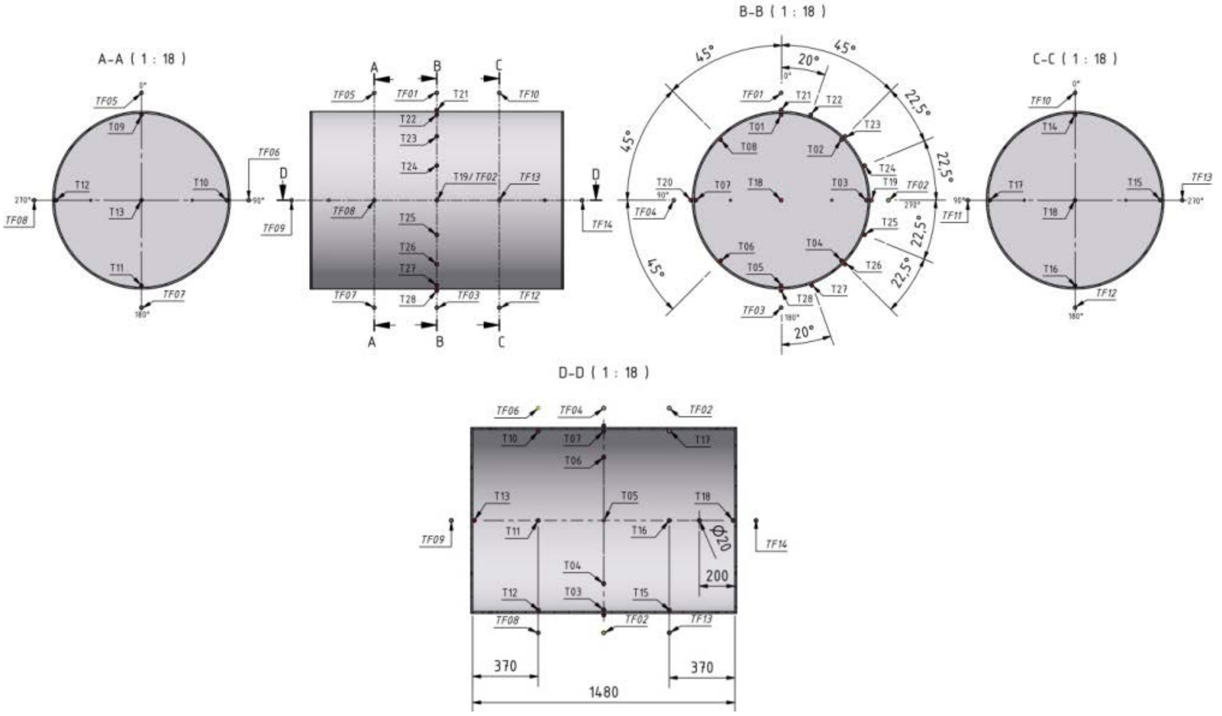


FIGURE 3. Instrumentation plan.

The instrumentation plan in Figure 3 shows the distribution of the thermocouples at the reference package. In total, 18 thermocouples (measuring points T1 to T18) were installed at the inner surface, 10 thermocouples (measuring points T19 to T28) at the outer surface and 6 thermocouples (measuring points TF1 to TF6) in a distance of 100 mm from the outer surface for measuring the flame temperatures.

Test set up

The BAM fire test facility with its two fire test stands A and B was built in 2004 for testing transport packages and waste containers for radioactive material and other dangerous goods and is situated close to the corresponding 200 tons drop test facility at the BAM Test Side Technical Safety [7].

Fire test stand A, where the calorimeter tests were performed, is mainly built of a flat concrete trough of 12 m x 8 m with a horizontal ring burner system and surrounded by wind shields. The test specimen is usually placed on a water cooled rig in the middle of the trough. The fire engulfment is realized by burning propane which is released horizontally in liquid state from a multitude of gas nozzles in a pipe that surrounds the test specimen in form of a ring burner. The geometry of the ring burner can be adapted to the dimensions of the test specimen in order to get full fire engulfment. The heating output can be regulated by variating the mass flux of the propane and the number of nozzles. The fire peak temperatures reach 1100 °C. The effect of side wind can be regulated using 2,500 mm high wind deflector plates made of heat-resistant steel sheets surrounding the trough with 16 m x 12 m. A permanent water circulation system cools pipes and concrete trough.

Figure 4 shows the current test setup for the calorimeter test in fire test stand A. The ring burner with the dimensions of 5,000 mm x 4,000 mm was installed in a height of 500 mm from the ground and equipped with 8 gas nozzles at each long side and 4 gas nozzles at each short side, which means 24 nozzles in total. The reference package was placed on a rig so that the distance from the lower side of the package to the ground was 850 mm. The propane gas volume flow was set to constantly 1,800 kg/h in all three tests.

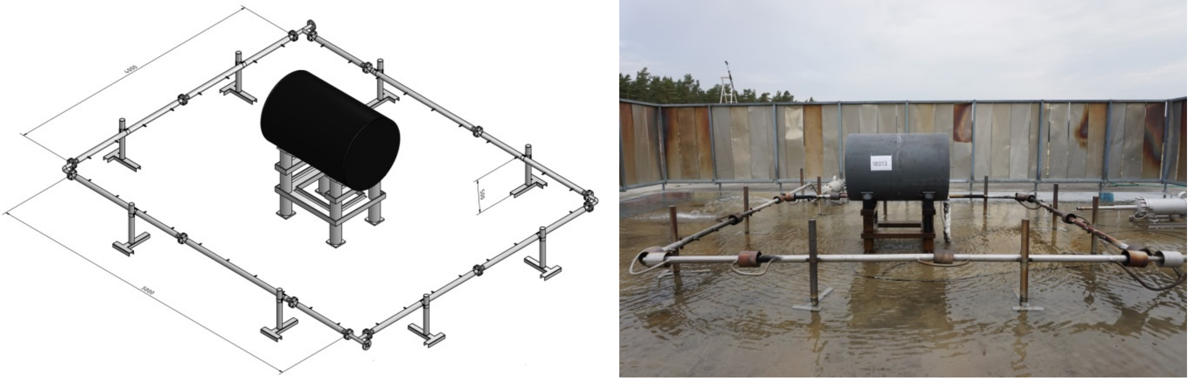


FIGURE 4. Schematic test setup and original fire test stand A with fire reference package ready for fire testing.

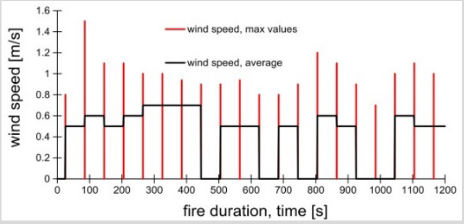
Fire test performance

The fire tests were conducted in three consecutive days at the end of August 2018 without any rain. They were performed during the early morning time between 7 am and 8 am when wind generally doesn’t appear at the area of the test stand or is slightly light. Nevertheless, it happened that we had various wind conditions during the tests (see Table 1). As an example Figure 5 shows the reference package at two single time points during the fire test and the influence of the wind to the completeness of flame engulfment.

During the tests the fire temperatures, package temperatures, propane gas flow and weather conditions (wind speed, wind direction, etc.) were recorded versus time. Additionally, videos were taken from two different points of view in order to document and later analyze the flame engulfment.

FIGURE 5. Typical flame engulfment situations during test no 18011.

TABLE 1: Wind conditions and diagram with wind speed vs fire duration relating to test no 18011.

test	wind speed	main wind direction	
18010	1.4 – 2.8 m/s	south-west to north-west	
18011	0 – 0.7 m/s	south-south-west	
18013	0.8 – 2.4 m/s	east-north-east	

Model for heat flux calculation

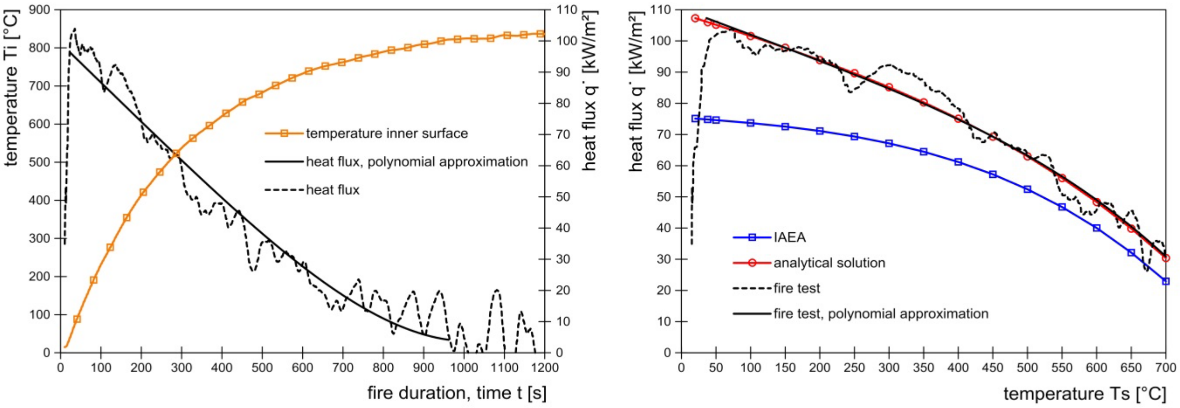
With the temperatures measured the local and overall integral heat flux into the fire reference package can be calculated. Therefore, the temperatures measured at the inner surface of the inner wall, as shown in Figure 2, were used. Some assumptions and the basic model for the calculations will be presented in the following. For the calculation of the heat flux, the energy balance for a defined volume was considered according to the following equation [8]:

$$\dot{q}[c_p(T), T(t)] = \frac{m}{A}\, c_p(T)\, \frac{dT(t)}{dt} \qquad (1)$$

The equation expresses that the inner energy of a volume element increases, if the heat flux leaving the volume is lower than the heat flux entering the volume [9]. We assumed in the calculation a cube with the side length of 10 mm. This cube represents a simplified part of the fire reference package shell. The temperature of the cube $T(t)$ was measured close to the isolated inner wall and assumed to be homogeneous in the cube. So, the surface temperature $T_s(t)$ of the cube is assumed to be equal to the measured inner wall temperature of the shell $T_i(t)$. A temperature gradient in the shell as shown in [4] is neglected in the presented calculations. A Finite-Element-Analysis has shown the maximum temperature gradient in the shell being less than 7 K considering the heat flux from the ‘IAEA-curve’. The inner wall is assumed to be adiabatic due to the insulation. The sidewalls of the cube are also assumed to be adiabatic as it is assumed that the adjacent volumes have the same heat input. So, heat conduction through the fire reference package is assumed to be one-directional, even though a lateral heat flow in the shell occurs and a temperature adjustment takes place. Nevertheless, the measured temperatures at the different thermocouple locations showed differences at the end of the fire phase. With this basic model, the measured temperatures were used to calculate an arithmetic average heat flux and local heat fluxes as presented in the subsequent chapter.

Experimental results

In the following and as an example, the specific results of test no. 18011 are described. The results are mainly founded on the originally measured temperatures-time-curves at the inner surface of the reference package. The diagram in Figure 6 shows the average temperature curve versus fire duration *t* calculated from the measured temperatures of all 18 thermocouples placed at the inner surface of the package wall. The temperatures are constantly increasing and reaching a maximum value of 830 °C. Based on the temperature changes $dT(t)/dt$ at the wall, the corresponding heat flux $\dot{q}$ into the package, also shown in the diagram of Figure 6 was numerically calculated according to equation (1). For the specific heat capacity in dependency of temperature $c_p(T)$ a best fit straight line through the $[T, c_p]$-value points taken from [10] was used up to 800 °C and neglecting the curie phase change. In [11], the curie phase change of carbon steel was found to be the greatest contributor of heat flux uncertainty occurring with the calorimeter being in the temperature range between around 725 °C and 764 °C. The results presented focus mainly on surface temperatures below that range. At the beginning of the fire, the overall integral heat flux into the package starts with a value of approximately 100 kW/m² and the corresponding inner surface temperatures are still low. Further, with increasing package temperature and becoming alike to the fire temperatures the heat flux reduces continuously to zero.



FIGURES 6, 7: Measured inner surface temperature and heat flux *vs* time, Overall integral heat flux *vs* outer average surface temperature.

The diagram in Figure 7 shows the connection between the overall integral heat flux $\dot{q}$ and the average outer surface temperature T_S of the reference package. It has to be remarked, that the measured outer temperatures were overlaid by the flame temperatures so that the inner surface temperatures were used instead. Here the assumption was made that inner and outer temperatures are the same due to the thin wall thickness of the package as mentioned in the previous chapter. The fire test shows, that for surface temperatures up to 125 °C a maximum heat flux of 100 kW/m² occurred which then declines in a function of fourth order by increasing surface temperatures. The corresponding analytical solution, developed in the subsequent chapter, complies very well with the experiment. The heat flux in the experiment exceeds the 'IAEA-curve' throughout the whole surface temperature range.

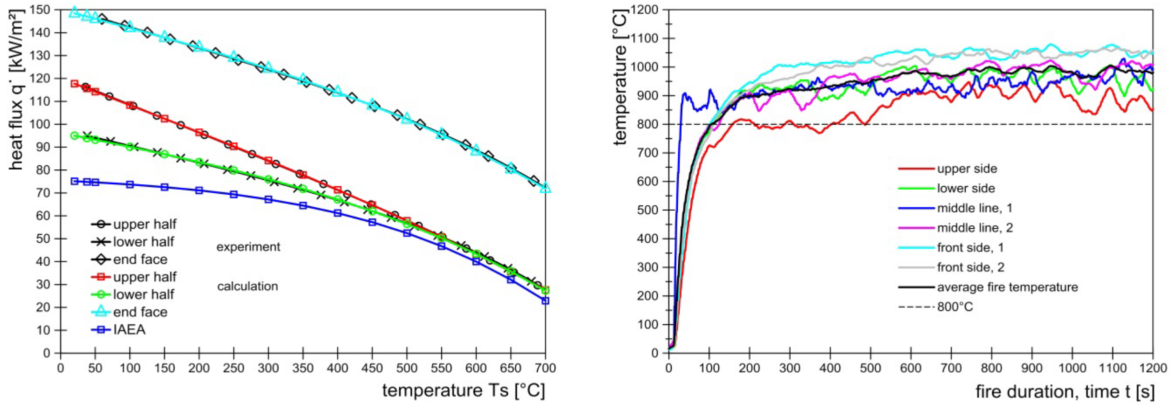


FIGURE 8, 9: Local integral heat flux vs relating outer average surface temperature, Fire temperatures.

Another point of interest was the distribution of the overall integral heat flux to various local parts of the package. For that, the upper half, the lower half, and the end faces of the package were selected. The end face-curve was determined with the 2 thermocouple temperatures in the middle of the circular end faces (T13 and T18 - Figure 3). The upper half-curve and the lower half-curve were each determined with 11 measured thermocouple data. So, in both curves the measured temperatures of the middle layer were considered. Analogues to the determination of the overall heat flux, the local heat fluxes were calculated, here on base of the average inner temperatures of each part according to equation (1). The diagram in Figure 8 shows the local heat fluxes versus surface temperature for each selected part of the reference package with the corresponding analytical solution. All local heat flux curves match the 'IAEA-curve'. Over all measuring points, the fire temperatures laid between 800 °C and 1100 °C, where the temperatures at the front sides showed the highest values with 1000 °C and more. The heat flux into the end faces of the package was significantly high (maximum value 150 kW/m²) during the whole upraising surface temperature relating to upper (maximum value 120 kW/m²) and lower half (maximum value 95 kW/m²). Also the heat fluxes of upper and lower half differ from each other. Up to a surface temperature of 450 °C the heat flux into the upper half of the package is higher than into the lower half. The differences of the curve characteristics in Figure 8 can be described with locally differing fire characteristics.

Calculation of fire characteristics

Beside the clear definition of a pool fire, the IAEA documents specify different parameters in [1] and [2] to define the IAEA fire phase. Taking these parameters into account, a specific heat flux through the surface of a specimen can be determined in dependence of the surface temperature. This 'IAEA- curve' is shown in Figure 7. In the shown curve a radiation exchange coefficient between the flames and the surface is proposed to be based on the special case of radiation exchange between two parallel plates [9]:

$$\boldsymbol{\varepsilon_e = \frac{1}{\frac{1}{\varepsilon_f}+\frac{1}{\varepsilon_s}-1}} \qquad (2)$$

With the maximum achievable value of $\varepsilon_s = 1$ for the surface emissivity, the flame emissivity $\varepsilon_f = 0.9$ given in [1] and with formula (2) a value of $\varepsilon_e = 0.9$ results. For the convective heat transfer during the fire phase a value of $\alpha = 10\,\frac{\mathrm{W}}{\mathrm{m^2K}}$ is specified in [2]. The temperature given in [1] and [2] is an average fire temperature of $T_f = 800°\mathrm{C}$. The fire is fully engulfing the specimen. With these given parameters the heat flux into the package can be described in dependence of the surface temperature as follows:

$$\boldsymbol{\dot{q}[T_S(t)] = \varepsilon_e\,\sigma\,\left(T_f^4 - T_s^4(t)\right) + \alpha\,(T_f - T_s(t))} \qquad (3)$$

The formula describes the heat transfer as combination of convection and radiation. It's visible in Figure 7 how the heat flux of the 'IAEA-curve' decreases with an increasing surface temperature. Furthermore, the measured heat flux and the resulting polynomial approximation are shown in Figure 7. Also, an analytical solution for the measured heat transfer is presented in Figure 7. The calculation of it will be shown here. The analytical solution is calculated based on the polynomial function via calculating the effective flame temperature, the fire convection coefficient, and the radiation exchange coefficient. These 3 parameters - the fire characteristics - are assumed to be constant during the whole test for the proposed calculation, although they are not in a real fire. The effective flame temperature for instance, that yields the correct heat transfer to the package, can change in dependency of the surface temperature as discussed in [12]. A temperature change is also visible in the development of the average fire temperature in Figure 9. The effective flame emissivity and the convection coefficient change over time due to the highly turbulent fire as visible in Figure 5. Furthermore, the emissivity of the surface might change for instance because of surface sooting as mentioned in [2].

A solution for these 3 unknown parameters based on the polynomial function shown in Figure 7 was calculated. For that, 3 equations were set with equation (3) and its values for the heat flux at 3 defined surface temperatures of the polynomial function $\dot{q}[150°\mathrm{C}], \dot{q}[450°\mathrm{C}]$ and $\dot{q}[750°\mathrm{C}]$. Solving these 3 equations leads to the calculated values of $\varepsilon_e = 0.63$ for the radiation exchange coefficient, $\alpha = 66.2 \frac{\mathrm{W}}{\mathrm{m}^2\mathrm{K}}$ for the convection coefficient and $\mathrm{T}_\mathrm{f} = 833.1°\mathrm{C}$ for the effective flame temperature (Table 2). The analytical solution shown in Figure 7 is defined with these fire characteristics and equation (3). The polynomial approximation and the analytical solution in Figure 7 are very close to each other and cross at the surface temperatures of 150 °C, 450 °C and 750 °C. The calculated values seem physically plausible. The calculated effective flame temperature fits to the average temperature, the inner surface temperature curve is approximating in Figure 6. The radiation exchange coefficient calculated here differs just slightly from the radiation exchange coefficient calculated with equation (2) to $\varepsilon_\mathrm{e} = 0.73$ considering the flame emissivity $\varepsilon_f = 0.9$ and the standard value of $\varepsilon_\mathrm{s} = 0.8$ given in [1] and [2].

The same calculation procedure was applied to the polynomial approximations shown in Figure 8. The results are shown in Figure 8 and Table 2. As a result, it seems obvious that the overall effective flame temperature of 800 °C is reached in average. Furthermore, the convective heat transfer coefficient in the propane gas fire test facility calculated here is higher than the proposed value in [2]. The radiation exchange coefficients do not reach the maximum proposed values in [1] and [2]. The overall heat flux as well as the segmentally determined heat flux of the presented fire reference package test covers the calculated 'IAEA-curve' over the whole range of surface temperatures as visible in Figure 7 and Figure 8.

TABLE 2: Calculated fire characteristics.

	overall integral (fig.7)	upper half (fig.8)	lower half (fig.8)	end faces (fig. 8)
Effective flame temperature T_f [°C]	833.1	855.5	832.6	1003.0
Radiation exchange coefficient ε_e	0.633	0.236	0.585	0.489
Convection coefficient α $[\frac{\mathrm{W}}{\mathrm{m}^2\mathrm{K}}]$	66.2	115.0	56.2	76.5

Conclusion

- A fire reference package could be designed to measure temperatures and determine local as well as global heat fluxes from a propane gas fire into the package in dependence of the surface temperature.
- A method to compare the propane gas fire with the IAEA fire over a wide range of surface temperatures is proposed.
- A calculation is proposed to determine fire characteristics with the measured heat flux for comparison with the IAEA-fire. The approach gives physically plausible results as an effective flame temperature of $\mathrm{T}_\mathrm{f} = 833.1°\mathrm{C}$, a radiation exchange coefficient of $\varepsilon_\mathrm{e} = 0.63$ and a convection coefficient of $\alpha = 66.2 \frac{\mathrm{W}}{\mathrm{m}^2\mathrm{K}}$.
- The results provide an initial picture of local fire characteristics of the propane gas fire test facility.
- The test shows that the propane gas fire covers the IAEA heat flux for numerical calculations over a wide range of surface temperatures with the chosen test stand parameters.

Nomenclature

$\dot{q}$ … heat flux $[\frac{W}{m^2}]$

m … mass [kg]

t … time [s]

c_p … specific heat at constant pressure $[\frac{J}{kgK}]$

T … Temperature [°C]

T_s … surface Temperature [°C]

T_i … inner wall temperature [°C]

T_f … effective flame Temperature [°C]

σ … Stefan − Boltzmann constant $[\frac{W}{m^2K^4}]$

ε_s … surface emissivity [1]

ε_f … effective flame emissivity [1]

ε_e … radiation exchange coefficient [1]

α … convection coefficient $[\frac{W}{m^2K}]$

References

[1] IAEA Safety Standard for protecting people and the environment. Regulations for the Safe Transport of Radioactive Material – 2018 Edition, IAEA Safety Standards Series No. SSR-6 (Rev.1), IAEA 2018

[2] IAEA Safety Standard Series. Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material– 2012 Edition, Specific safety Guide No. SSG-26, IAEA 2014

[3] N.R. Keltner, J. L. Moya; Defining the Thermal Environment in Fire Tests; Fire and Materials, vol. 14, 133-138 (1989)

[4] Beck, J. V. and Wolf, H., The Nonlinear Inverse heat Conduction Problem, ASME Paper 65-HT-40, presented at the ASME/AIChE Heat Transfer Conference an Exhibit, Los Angeles, CA, August 8-11, 1965

[5] M. Alex Kramer, Miles Greiner, J. A. Koski, Carlos Lopez, Ahti Suo-Anttila; Measurements of Heat Transfer to a Massive Cylindrical Calorimeter Engulfed in a Circular Pool Fire; Journal of Heat Transfer; 2003

[6] B. Droste, G. Wieser, U. Probst; Thermal test requirements and their verification by different test methods PATRAM 1992, Yokohama, Japan

[7] B. Droste, A. Ullrich and J. Borch; Brand new fire test facilities at “BAM Test Site Technical Safety”; Packaging,Transport, Storage & Security of Radioactive Material, Volume 22, Number 4, pp. 195-199, Maney Publishing (2012)

[8] Handbook of Heat Transfer; W. M. Rohsenow, J. P. Hartnett, Y. I. Cho; McGraw-Hill Handbooks; Third edition; 1998

[9] VDI-Wärmeatlas; Verein deutscher Ingenieure VDI-Gesellschaft Verfahrenstechnik und Chemieingenieurwesen (GVC); Springer; 10. Auflage 2006

[10] Stahl-Eisen-Werkstoffblätter (SEW) des Vereins Deutscher Eisenhüttenleute, Verlag Stahleisen

[11] M. Alex Kramer, M. A. del Valle, M. Greiner; Measurement and Uncertainty of Heat Flux to a Rail-Cask Size Pipe Calorimeter in a Pool Fire; 2008 ASME Pressure Vessels and Piping Division Conference; PVP2008-61600; Chicago, Illinois, USA

[12] J. A. Koski; Measurement of Temperature Distributions in Large Pool Fires with the use of Directional Flame Thermomenters; American Society of Mechanical Engineers, Pressure Vessels and Piping Division; PVP 408:111-115; January 2000