Heat Transfer Studies in Pool Fire Environment

F. Nitsche

Bundesamt für Strahlenschutz, Germany

INTRODUCTION

A Type B package has to withstand severe thermal accident conditions. To calculate the temperature behaviour of such a package in a real fire environment, heat transfer parameters simulating the effect of the fire are needed. For studying such heat transfer parameters, a systematic programme of experimental and theoretical investigations was performed which was part of the IAEA Coordinated Research Programme (Nitsche and Weiß 1990). The studies were done by means of small, unfinned and finned, steel model containers of simplified design in hydrocarbon fuel open fire tests. By using various methods, flame and container temperatures were measured and also container surface absorptivity before and after the test to study the effect of sooting and surface painting on heat transfer. Based on all these experimental data and comparative calculations, simplified, effective heat transfer parameters could be derived, simulating the effect of the real fire on the model containers.

OBJECTIVES AND INVESTIGATION PROGRAMME

For the thermal behaviour of a package in open fire, the heat flux $\dot{q}$ transferred from the flames to the package is of decisive importance. It is transferred by thermal radiation $\dot{q}_r$ and thermal convection $\dot{q}_c$ with the thermal radiation of the luminous flames playing the dominant role. In a simple model, this heat transfer can be formulated as follows:

$$\dot{q} = \dot{q}_r + \dot{q}_c = \sigma \cdot \in_C \cdot \in_F \cdot \phi_{CF} \cdot (T_F^4 - T_C^4) + \alpha_C (T_F - T_C) \quad (1)$$

where σ = Stefan-Boltzmann constant (5.67×10^{-8} W/m^{2}K^4)
$\in_C$ = absorptivity coefficient of packaging (container)
$\in_F$ = emissivity coefficient of flames
ϕ_{CF} = shape factor
T_F = flame temperature (in K)
T_C = packaging (container) surface temperature (in K)
α_C = convective heat transfer coefficient

The application of this simple model requires the determination of suitable representative mean values for the heat transfer parameters T_F, $\in_F$, $\in_C$, α_C by which the time-dependent thermal behaviour $T_C(t)$ in a real fire environment can be simulated. For studying these heat transfer parameters model tests in open hydrocarbon fires were performed. A small steel model container of simple design and geometry was used whose thermal behaviour can be exactly calculated for a given heat flux. To calculate $T_C(t)$, a special computer program was used, for which the heat transfer parameters to be determined (T_F, $\in_F$, $\in_C$, α_C) represent variable input data. By comparing the calculated container temperatures with the measured ones in the real fire environment the characteristic heat transfer parameters according to (1) can be derived. In this respect it has to be taken into account that different value combinations of these parameters can be found resulting in the same thermal behaviour $T_C(t)$. Therefore it was attempted to find out well defined values for the individual parameters by using special additional measurements ($\in_F$- and $\in_C$-measurement as described in (Nitsche and Weiß 1987)) and by performing a systematic experimental test programme with different model containers according to the following steps:

1. Measurement of the thermal behaviour of a cylindrical unfinned model container (steel container, 43 kg mass) in open fire and comparison with calculations,

2. Measurement of the thermal behaviour of the finned cylindrical model container (same steel container like 1. with 36 welded steel fins, 49.5 kg mass) with clean and painted surface in open fire and comparison with calculations, and

3. Measurement of the thermal behaviour of a larger, cylindrical unfinned model container (steel container, 248 kg mass) and comparison with calculations, especially to study the effect of container surface absorptivity (sooting) on heat transfer.

The experimental arrangements for the three model containers are shown schematically in Figs. 1 to 4 and Fig. 7. All tests were carried out in the same way in a large fire testing room of 20 m length, 10 m width and 5 m height having various controllable openings for air supply and exhaustion of smoke gases.

The pool fire was produced by diesel-fuel and fully engulfed the model container. Numerous thermocouples were used to measure flame temperatures and container wall temperatures. They were installed at selected measuring points in the fire environment as well as inside and outside the model container to obtain representative temperatures of the fire and the model container (see Figs. 1 to 4 and Fig. 7), as is necessary for comparative calculations. Special measuring techniques were applied to get small temperature measuring errors (Nitsche and Weiß 1987). The model containers were always positioned in the hot center of the pool fire to get a fire environment as homogeneous as possible. To compare the experiments with calculations, the measured local and temporal flame temperatures were averaged to obtain mean flame temperatures.

The experimental setup and measuring equipment used as well as the computer program and comparative calculation model applied are described in detail in (Nitsche and Weiß 1990 and 1987).

RESULTS FOR UNFINNED MODEL CONTAINER

Two tests were performed resulting in mean flame temperatures ($\overline{T}_F$) of 1125°C ad 1170°C. Before each test the surface of the model container was sooted uniformly to obtain a defined initial value for the container absorptivity coefficient. The absorptivity was measured before and again after the test (Nitsche and Weiß 1987).

Good agreement between measured and calculated container wall temperatures was found, as can be seen from Fig. 5, inserting the measured $\overline{T}_F$-values as flame temperatures into the computer calculations. For the other effective heat transfer parameters according to (1), the following values were found for both tests:

$$\epsilon_F = 0.9$$
$$\epsilon_C = 0.6$$
$$\alpha_C = 25\ \mathrm{W/m^2K}$$

These values of ϵ_F and ϵ_C derived from comparative calculations are supported by the results from the experimental investigations of ϵ_F and ϵ_C as described in (Nitsche and Weiß 1987).

RESULTS FOR FINNED MODEL CONTAINER

Two tests were performed in the same way as for the unfinned container resulting in mean flame temperatures of 1085°C and 1103°C. Using these temperatures for comparative calculations and taking into account the effect of the fins by a special shape factor (see (1)) in the radiant heat transfer calculations (Nitsche and Weiß 1990) again good agreement between measurement and calculation was found as shown in Fig.6.

This result confirms the heat transfer model and derived parameters obtained in the case of the unfinned model container. The slightly lower absorptivity value of 0.55 could result in the fact that due to the high temperature of the fins the soot layer is burned off faster than in the case of the unfinned container, leading to cleaner fin surface and therefore to a lower effective absorptivity value for the finned model container.

To study the effect of surface absorptivity on the heat transfer the finned model container was painted with a 3-layer coat and then exposed to the same fire test conditions as before. In this case the following mean values for the container absorptivity were derived by comparative calculations:

1. test: $\epsilon_c = 0.95$, paint still maintained after the 1. test
2. test: $\epsilon_c = 0.7$, paint only partially maintained after 2. test
3. test: $\epsilon_c = 0.6$ surface was cleaned (paint removed) before the 3. test, surface remains clean after the test

Some of these data could be supported by measurements of the absorptivity before and after the test, where for the 1. test an absorptivity value of 0.98 was measured before the test and 0.91 after the test.

RESULTS FOR LARGER UNFINNED MODEL CONTAINER

Tests were made in the third stage of the programme in order to confirm the heat transfer parameters at the somewhat larger model container. Especially the sooting of the container surface, which takes place in an open hydrocarbon fire, and its effect on heat transfer was studied. The sooting of the model container in the fire environment could be demonstrated by performing 4 tests with different fire durations:

Test number	Mean flame temperature T_F/°C	Fire duration t_F/min	Container Surface temperature/°C	Surface State
1	951	5	~ 250	covered with soot
2	980	8	~ 300	covered with soot
3	951	11,5	~ 370	covered with soot
4	980	16	~ 600	partially sooted and partially metallic clean

The temperature response of the model container for tests No. 1, 2 and 4 is shown in Fig. 7. The state of the metallic container surface before the first test can be described as covered with a thin layer of rust. The absorptivity of the sooted surface was measured and a value of $\in_c = 0.95$ was obtained.

In the last test the surface temperature was high enough to get again a clean surface by burning off the soot. This soot-burn off temperature was found to be about 600°C under the described test conditions, which seems to be a rather high value.

Based on the measured mean flame temperatures, comparative calculations were also performed as in the case of the smaller model containers. Again good agreement between measured and calculated container temperatures was obtained as shown in Fig. 7, with the following effective heat transfer parameters for all four tests:

$\in_F = 0.9$

$\in_C = 0.95$ (corresponds with the measured value)

$\alpha_C = 25\ \mathrm{W/m^2K}$

These parameters correspond very well with the flame emissivities and convective heat transfer coefficients derived earlier for the smaller model containers.

The calculations showed further that depending on fire duration the soot layer effect on heat transfer has to be considered. In the short duration test number 1, e.g., the soot layer had no effect on heat transfer. On the other hand, in the tests number 2 to 4, it was found that the effect of the soot layer must be taken into account, resulting in a reduction of the heat flux from the flames to the model container due to the high soot-burn off temperature found under the given test conditions.

CONCLUSIONS

From the results obtained, the following main conclusions can be drawn concerning the practical performance of fire tests as well as the theoretical modeling of heat transfer processes:

To ensure a fire fully engulfing the container with a flame emissivity of not less than 0.9, a fire ground area of not less than 3 x 3 m^2 should be chosen and the pool size is required to extend not less than 1.50 m beyond the edges of the package.

For all fire tests performed with the small model containers the real fire environment can be characterized by a mean flame temperature $\overline{T}_F$ measured by thermocouples near the container surface. By comparative calculations with the computer program, the following effective heat transfer parameters simulating the effect of the fire environment were found:

a) mean fire temperature: $\overline{T}_F$
b) mean flame emissivity: $\in_F = 0.9$
c) mean absorptivity of container surface:
   unfinned model container: $\in_C = 0.6$ (metallic surface)
   finned model container: $\in_C = 0.55$ (metallic surface), $\in_C = 0.95$ (painted surface)
   larger unfinned model container: $\in_C = 0.95$ (sooted surface)
d) convective heat transfer coefficient: $\alpha_C = 25\ W/m^2K$

Based on all results of the programme, these parameters, a), b) and d), seem to be qualified to characterize the heat transfer to small packages in open pool fires. The prediction of the package surface absorptivity remains difficult because it depends on package surface state, material, design, temperature and fire conditions and therefore varies during the fire duration. It was found that sooting of package surfaces during the fire test has to be taken into account for realistic temperature prediction. For the given test conditions a high soot-burn off temperature of 600°C was obtained, resulting in a reduction of the heat flux from the flames to the package. These phenomena can have a significant effect on heat transfer for large packages in open fire.

References

Nitsche, F.; Weiß, M.
Heat Transfer Investigations for the Temperature Prediction of Packages in Real Fire,
IAEA Research Coordination Meeting, Buenos Aires, Juni 1990
Nitsche F.; Weiß, M.
Investigations of the Thermal Behaviour of Type B Packagings for Radioactive Materials in Real Fire,
IAEA Research Coordination Meeting, Tokio, September 1987

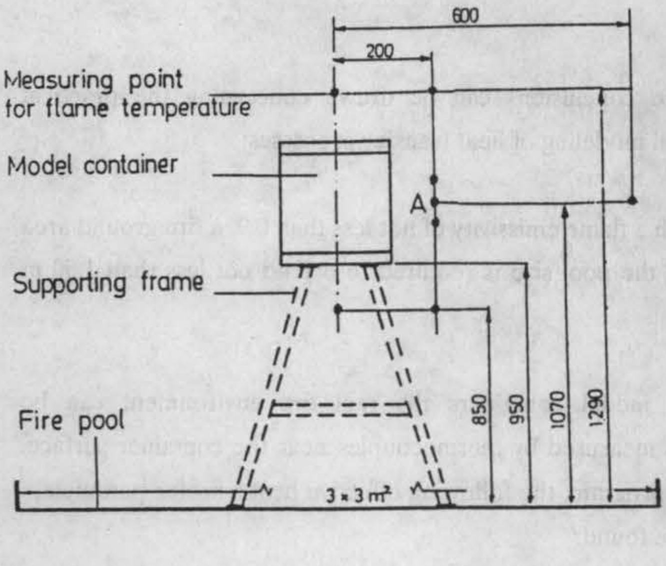


Fig. 1: Schematic representation of experimental setup with temperature measuring points in fire

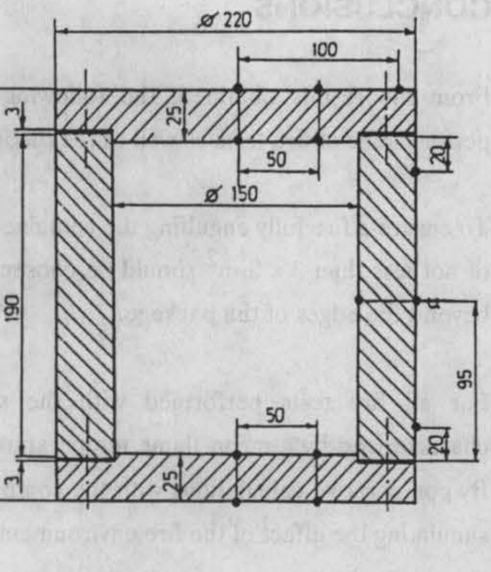


Fig. 2: Sectional view of model container with temperature measuring points

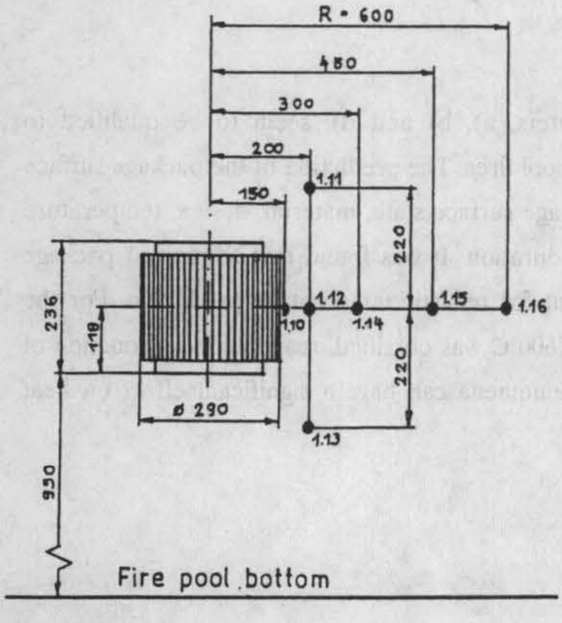


Fig. 3: Experimental arrangement for the finned model container with temperature measuring points in fire (•)

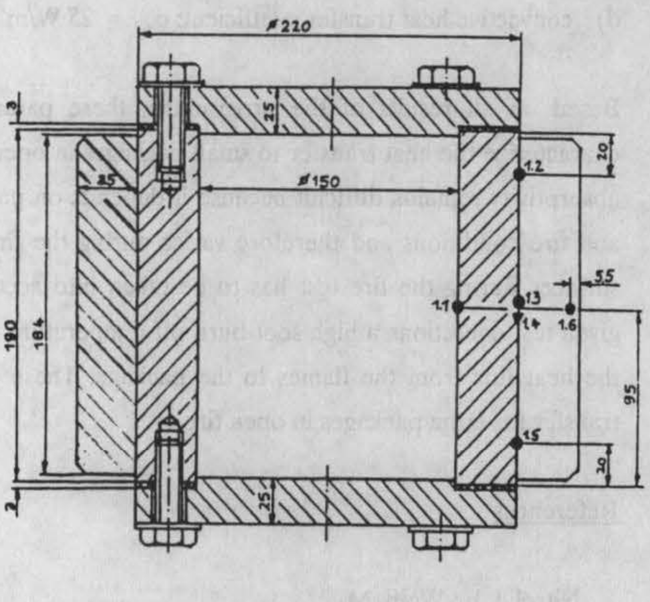
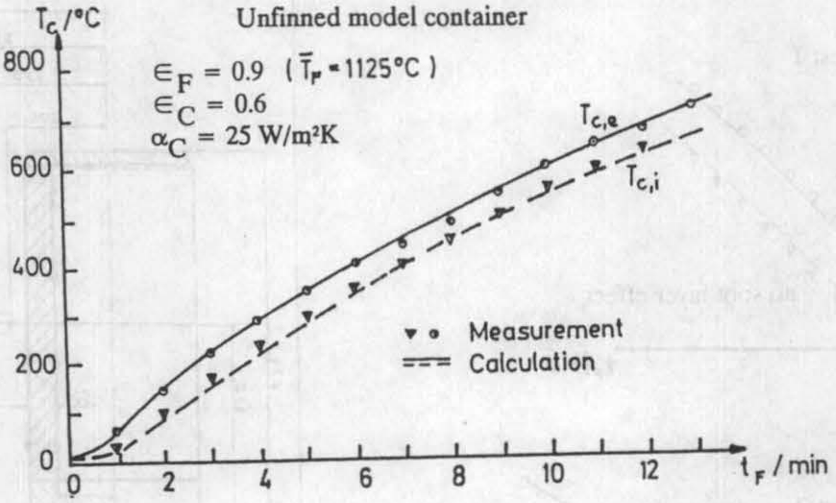
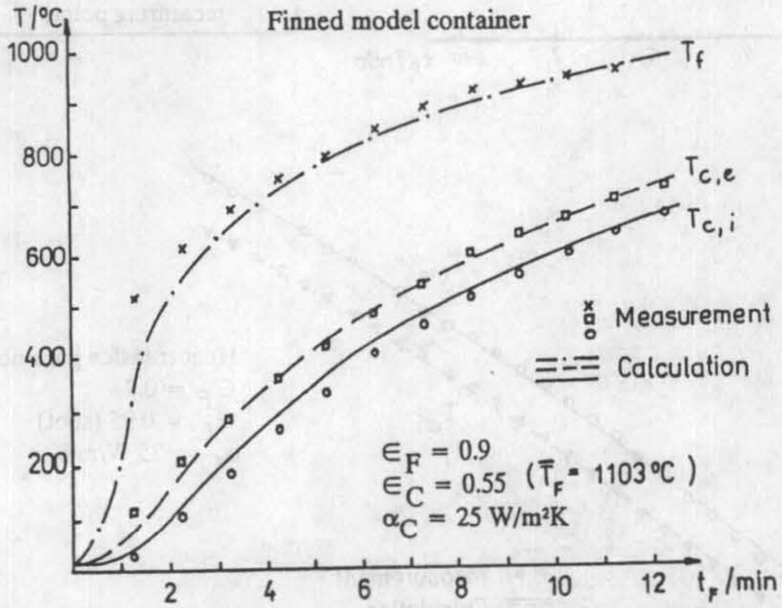


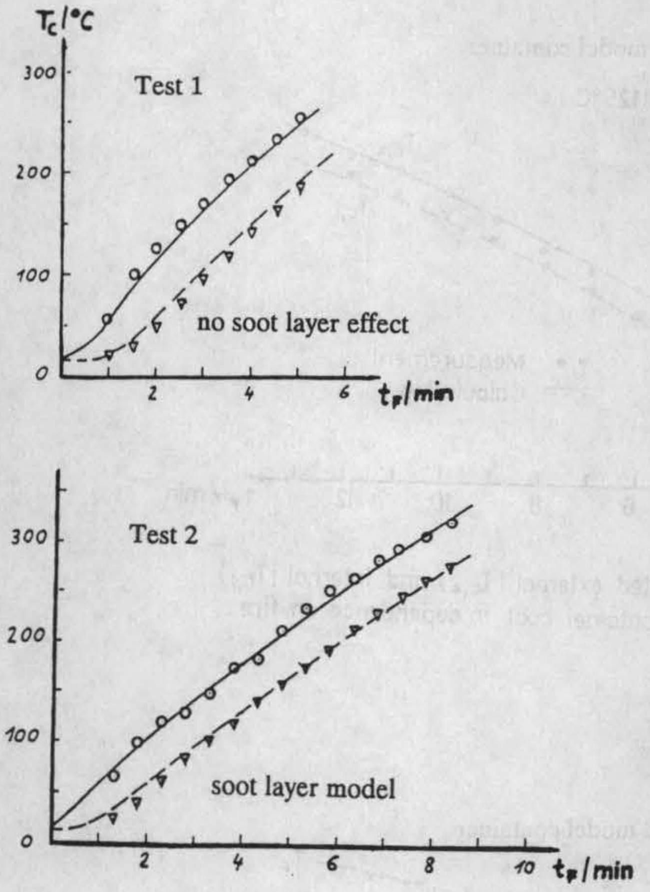
Fig. 4: Sectional view of the finned model container with temperature measuring points (•)

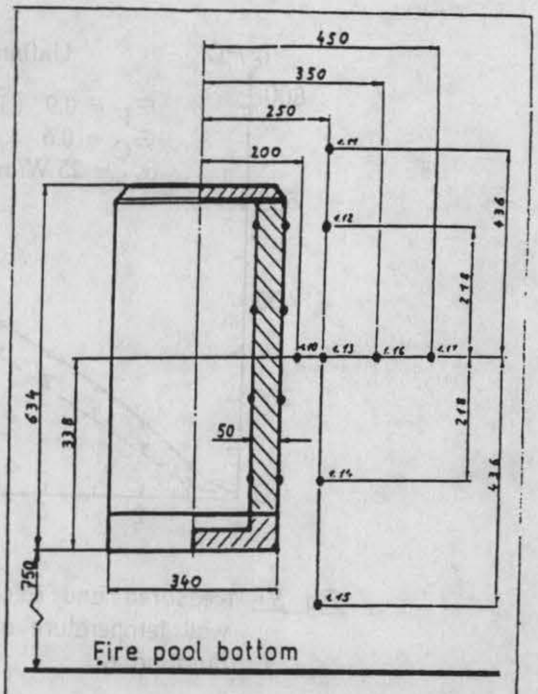


<u>Fig. 5:</u> Measured and calculated external ($T_{c,e}$) and internal ($T_{c,i}$) wall temperature of container coat in dependence on fire duration t_F

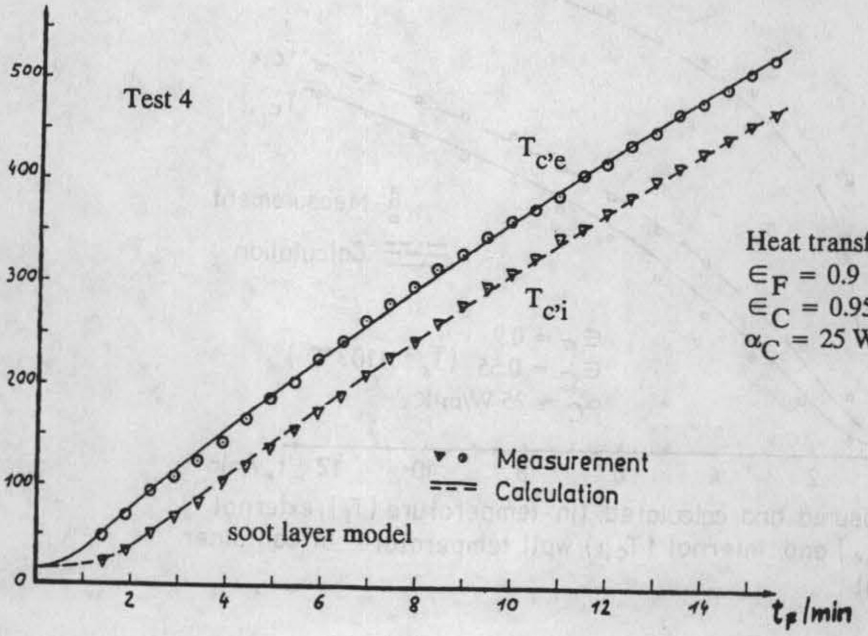


<u>Fig. 6:</u> Measured and calculated fin-temperature (T_f), external ($T_{c,e}$) and internal ($T_{c,i}$) wall temperature of container coat





Experimental arrangement for the larger model container with temperature measuring points



Heat transfer parameters for all tests:
$\epsilon_F = 0.9$
$\epsilon_C = 0.95$ (soot)
$\alpha_C = 25$ W/m²K

Fig. 7: Measured and calculated external ($T_{c',e}$) and internal ($T_{c',i}$) wall temperatures of larger model container for different fire durations (t_F)