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Fire Extinguishing Foam

- Test Method for Heat Exposure Characterisation

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Swedish National Testing and Research Institute
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Abstract

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The capability of fire fighting foams to resist heat radiation has been investigated in order to get a better understanding of the extinction mechanisms. Previous work identified a need to improve the measuring technique for drainage and foam destruction rate. The influence of foam layer thickness has also been investigated as well as the energy balance in the foam-fuel system during heat exposure.

The drainage rate measurements have been improved by the use of a measuring cylinder beneath the test vessel where the interface between the fuel and foam solution is recorded visually. The foam height measurement technique has also been improved making it possible to get an on-line measurement of the foam layer thickness and thereby a better possibility to determine the foam destruction rate as a function of time.

The "effective radiation" heat flux used was 42,6, 22,5 and 6,1 kW/m^2 in combination with a foam thickness of 25 mm, 50 mm and 100 mm. The evaporation rate measured, indicates an "evaporation constant" of 18-21 g/min, kW, i.e. that 80% - 90% of the energy is used for the evaporation of the foam.

The temperature measurements in the foam-fuel system show that about 5 - 8% of the total energy input is absorbed by the drainage. This is based on the total temperature increase of the fuel layer and the drained foam solution from start of radiation application until all the foam is destroyed and ignition occurs.

The drainage characteristic is dependent both on foam thickness and heat radiation. The drainage rate increases considerably already at low heat fluxes, reaches a maximum at moderate heat fluxes and is then reduced again at higher radiation.

The test method does not on its own provide the information why certain foams are more efficient than others. The method might however provide a part of the information needed and can provide data as input for modelling work. The repeatability is very good and it is relatively simple and fast to use.

Key words: Fire extinguishing foam, foam drainage, foam destruction, thermal radiation

Sveriges Provnings- och Forskningsinstitut
SP Rapport 1997:09
ISBN 91-7848-667-X
ISSN 0284-5172
Borås 1996

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SP Report 1997:09

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Preword

This research project has been sponsored by Nordtest and The Swedish National Testing and Research Institute (SP).

The aim of the project has been to improve the previous test methods presented in SP report 1992:54 [1].

The vast majority of the tests were executed by Erik Grahn, and the test set-up was constructed in cooperation with Joel Blom. The contributions by other members of the SP staff are also gratefully acknowledged.

1 Background

When a burning liquid is extinguished with fire fighting foams, there are several factors which influence the extinction. To get a better understanding of the extinction mechanisms, detailed studies of the various factors involved in the extinguishing process are needed.

The capability of fire fighting foams to resist heat radiation is one such factor which is of great importance. Previous work has been conducted measuring the resistance against heat radiation and the capability of the foam to suppress fuel vapours. This work was presented in SP-Report 1992:54 [1] and identified a need to further develop and refine the measuring techniques used. This pertains mainly to measurements of drainage rate and foam destruction rate.

In this project, further development of the test method and test equipment has been done. Tests have been made using the improved method on three different types of foam, three foam depths and three levels of heat radiation. Some tests with temperature measurements in the foam-fuel system were also performed in order to study the heat balance for the foam-fuel system.

A description of the testing equipment and test procedures to be used for future tests of this kind is presented in Annex A.

2 Development of the test procedure

One important parameter to study during heat exposure is the drainage rate. Expansion and drainage are the most commonly used parameters to characterise foams and standardised methods can be used. The method that will be most common in the future is specified in ISO 7203 [2] and prEN 1568 [3]. However, as the vessel used in the heat exposure tests in this project, differs from the one used for the standardised drainage tests, it was considered to be of interest to study the influence of different vessels and measuring techniques. This would allow for a correlation of the figures achieved by the various methods.

The original idea for the heat exposure tests was to measure the drainage rate from the foam applied on a fuel surface in a stainless steel pan. The pan was equipped with a rectangular side drain, 15 mm wide and 10 mm high allowing overflow of fuel, equal to the volume of drained foam, see figure 1. This was chosen because the liquid layer would then have a constant and well defined depth throughout the test. A similar method is described in part 2 of NT FIRE 023 [4].

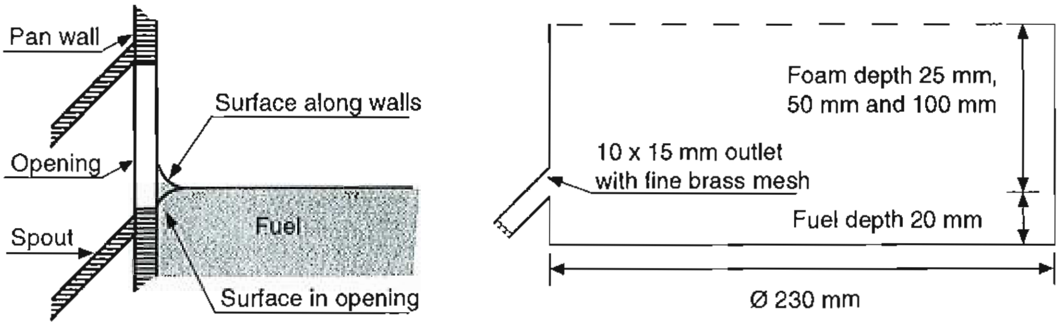


Figure 1 Sketch of the stainless steel pan with side drain and a detail of the fuel surface along the walls and at the overflow opening.

When using this procedure on a premix solution, the results looked promising, but when tests were repeated on a layer of heptane, there was a substantial time lag in the response and the repeatability was very bad, as shown in figure 2. Many different ways were tried to get around the problem. No solution that worked with reasonable consistency for the side drain vessel could be found and the method for measuring drainage was therefore changed.

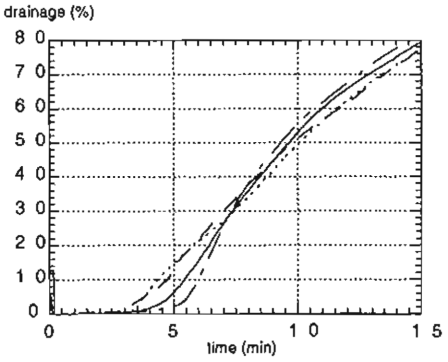


Figure 2 Four identical tests, measuring the drainage by having an outlet on the side of the drainage pan, show a very bad repeatability and a substantial time lag.

The problems seemed to be caused by surface tension effects. The vertical opening was a source of trouble. The fuel tended to creep up on the walls and at the same time tried to develop a cushion at the overflow edge as shown in figure 1. This caused a situation in the lower corners of the opening were the two different surface shapes had to join each other in a complex and unstable state of equilibrium. Surface tension alters between different fuels and foam types.

The vessels that were finally used during the heat exposure tests were instead equipped with measuring cylinders as shown in figure 3. A specific combination of vessel and cylinder was used for each foam thickness tested, see chapter 2.1. The vessel and cylinder were filled with fuel to achieve the desired foam thickness and the drainage was then measured by continuously making manual readings of the foam solution-fuel interface in the cylinder. The data could then be plotted as a function of time to achieve drainage rate curves.

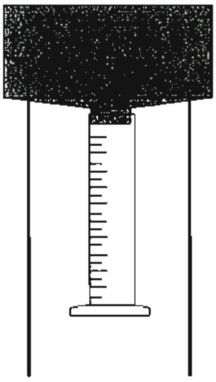


Figure 3 Final design of test vessel used in the heat exposure tests. The drained foam solution was collected in a measuring cylinder and the drainage rate was determined by visual readings.

2.1 Comparative drainage tests without heat exposure

The drainage characteristics was measured under six different conditions where drainage vessel and foam thickness was varied. The foam was generated using the small scale foam nozzle designated "UNI 86R" [5]. This nozzle was used during the entire project and is a small scale version of the test nozzle used in the ISO 7203 [2] and prEN 1568 [3] standards.

The first series of tests were made using the conventional "ISO-vessel" as shown in figure 4. This method requires manual control of the tap on the outlet. A second test series with an alternative equipment was therefore conducted. This method, which involves a vessel similar in size and shape to the ISO-vessel (see figures 4 and 5), is equipped with a filter in the bottom to replace the manually controlled tap. This method has been developed in the "FAIRFIRE" project [5] and is further described in SP report 1996:28 [6]. The drainage rate was in both test series recorded continuously with 5 seconds interval by a scale connected to a computer.

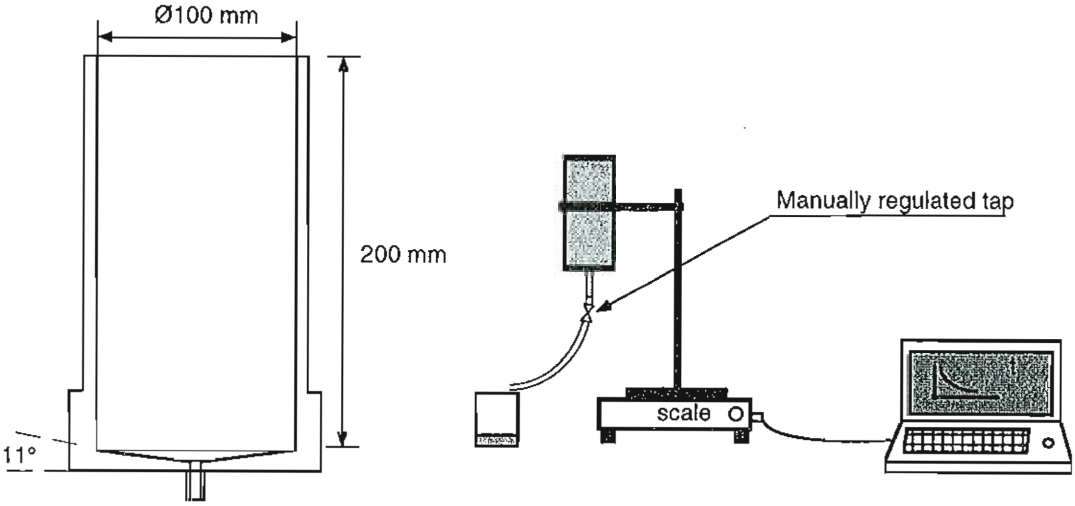


Figure 4 The ISO-vessel is equipped with a plastic hose and a tap which must be regulated manually during the test. The weight loss is recorded by a data logging system.

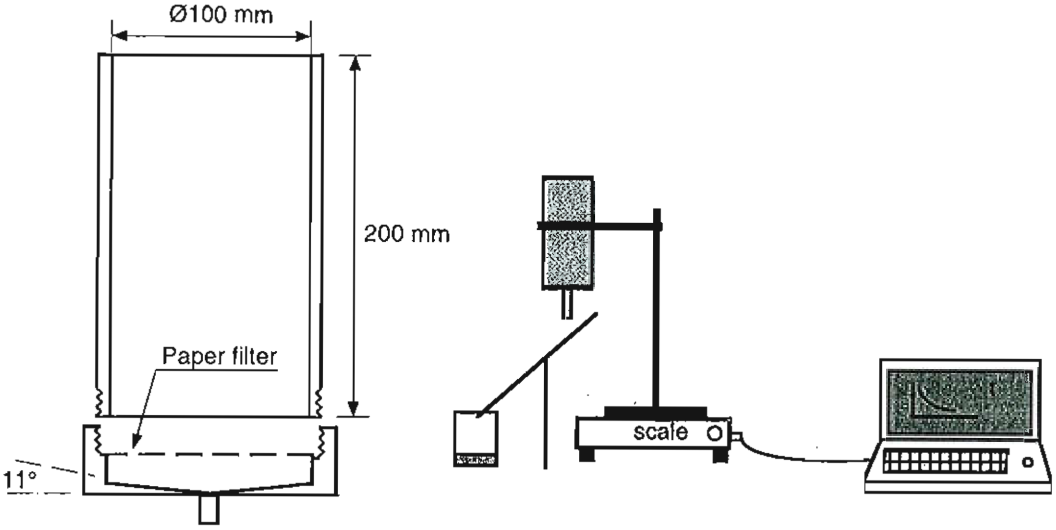


Figure 5 The re-designed ISO-vessel is equipped with a paper filter in the bottom which blocks foam but still allows the foam solution to pass. The weight loss is recorded by a data logging system.

The filter method was also used for a third test series were the foam was collected in a separate, larger vessel and then after about 1 minute of time delay was poured into the ISO-filter vessel. This was made to check the influence of this indirect filling procedure which had to be used in all of the heat exposure tests.

In the previous project [1] where the influence of heat exposure to foams was studied, a glass vessel, 230 mm in diameter, was used. This size was chosen since the radiation cone is 200 mm in diameter and no heating of the outside of the vessel was desired.

This test series therefore continued with such a glass vessel, 100 mm high, without any liquid bed, see figure 6. Tests were also made with the pan height extended to 200 mm by use of a sheet of plastic along the inside of the glass vessel. This was done in order to correlate with the 200 mm foam depth used in the ISO vessels. The pan was placed at an angle of 2° in order direct the drained solution to the outlet.

The drainage was manually controlled by a tap and the drainage rate was recorded continuously with 5 seconds interval by a scale connected to a computer.

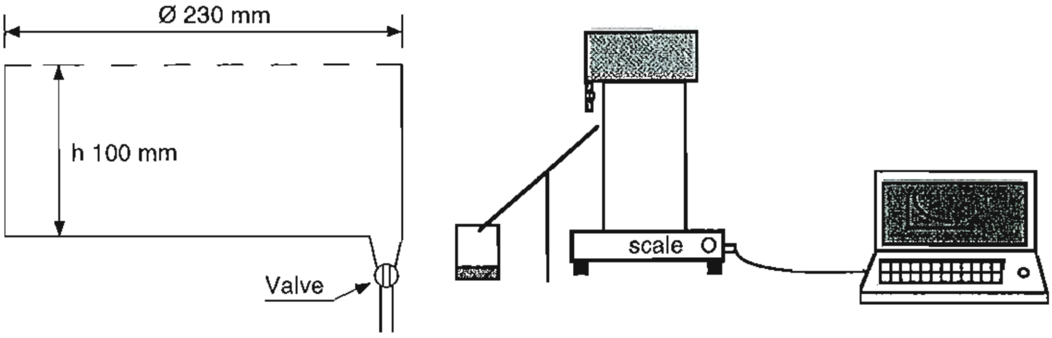


Figure 6 The glass vessel (100 and 200 mm high) was equipped with an outlet in the bottom and a tap which was regulated manually during the test. The weight loss was recorded by a data logging system.

The last test series for drainage characterisation was made on a fuel layer (heptane) in the stainless steel vessel used in the heat exposure tests as shown in figure 7. Three various vessel/measuring cylinder combinations were used for the three tested foam depths, 25, 50 and 100 mm, see table 1.

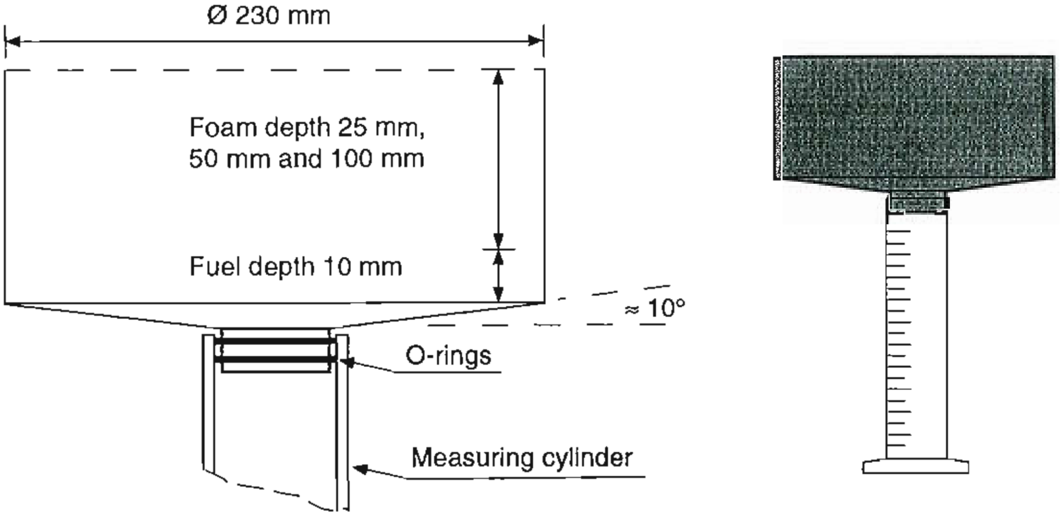


Figure 7 The final design of test vessel for the heat exposure tests was equipped with a measuring cylinder.

Table 1 Volumes of the different vessels, measuring cylinders and weight of the heptane used as fuel bed

Foam depth [mm]	Vessel volume [cm³]	Measuring cylinder size	Heptane weight [g]
25	2060	100	610
50	3220	250	740
100	6690	500	980

2.2 Results

Three different types of foam concentrate have been used in the project. The concentrates were a synthetic (S), a fluoroprotein (FP) and an alcohol resistant film forming foam (AFFF/AR). These foams, chosen to represent foams from the three different extinguishing classes specified in ISO 7203 and prEN 1568, have also been used in the "FAIRFIRE" project which means that there are substantial fire test data available [5]. All tests were performed with 3% concentration.

As the expansion value primarily is depending on the foam generation nozzle, expansion values are not reported specifically for each test. Typical expansion ratios for the three foams used during the tests are shown in table 2.

Table 2 Typical expansion ratios for the three foams used in the project. All tests were made with 3% concentration and the UNI 86R nozzle was used for foam generation.

Type of foam	Typical expansion ratios (±0.25)
Synthetic (S)	9.0
Fluoroprotein (FP)	7.5
Alcohol resistant AFFF (AFFF/AR)	8.0

In most cases duplicate tests were made for each test condition, in some cases triplicate tests were made. The repeatability was in general very good. In figure 8 all tests are summarised by plotting the average time to 25%, 50% and 75% drainage as a function of time. As shown in the graphs, the foams have different drainage characteristics where the synthetic foam is the most slowly draining, while the FP and AFFF/AR drain more rapidly. The figure also shows that the drainage method and equipment influences the results to some extent but without any dramatic differences. The most pronounced factor is the depth of the foam layer where a thinner foam layer gives a shorter time to 25 %, 50 % and 75% drainage. Only the tests with 100 mm foam depths in the final test configuration is shown in the figures (designated "steel-heptane") as these could be compared with the 100 mm tests in the glass vessel. These two results are almost identical which indicates that the fuel layer is not giving any considerable influence to the drainage rate. Under fire conditions, where the fuel is hot and there is a substantial vapour pressure, the foam behaviour might be different but this has not been investigated in this project.

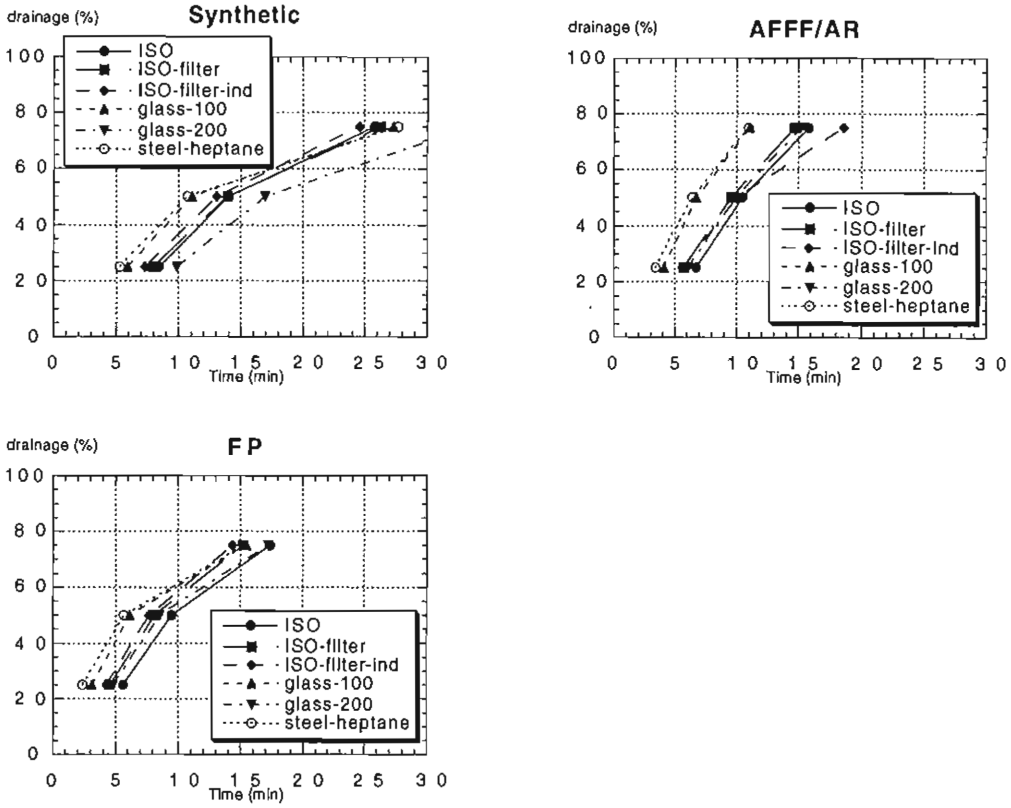


Figure 8 Graph showing time to 25%, 50% and 75% drainage as a function of time for all drainage tests made with the various drainage vessels and foam depths. "Steel-heptane" indicates the tests with 100 mm foam depth on heptane in the vessel used for the heat exposure tests

3 Heat exposure tests

3.1 Test set-up

Based on the preliminary characterisation of the drainage properties as described in chapter 2, a stainless steel vessel with bottom drain into a measuring cylinder was used for the heat exposure tests, see figure 7. The vessels were made for three depths of the foam layer, 25 mm, 50 mm and 100 mm with properties as shown in table 1. The bottom of the pan was sloped 10° towards the bottom outlet. On the outside of the outlet two grooves were made to hold O-rings for fixing a standard measuring glass to the pan. The foam solution-fuel interface was determined visually and the volume was recorded every 2,5 - 10 ml depending on the depth of the foam layer and thereby type of measuring cylinder used.

The vessel was placed on a scale connected to a data logging system in order to record the evaporation rate as shown figure 9. The radiation cone, supported on a separate stand, was mounted such that the distance was 20 mm from the cone down to the rim of the vessel as shown in figure 10. When the foam layer was destroyed such that heptane vapours could be released, these were ignited by a small propane pilot flame, positioned at the rim of the pan.

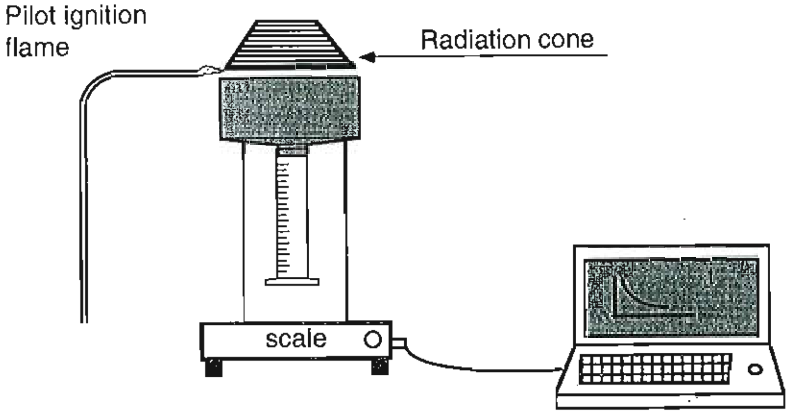


Figure 9 The vessel was placed on a scale connected to a data logging system in order to record the evaporation rate. Three various vessel were used for tests with various foam depths, 25 mm, 50 mm and 100 mm.

One of the main purposes of the project was also to improve the measurements of the foam destruction rate. A special equipment was therefore constructed to enable recording of the foam height when the foam was subjected to radiation, see figure 10. A linear potentiometer was connected via a lever to a horizontal cross made from thin steel wire. The signal from the potentiometer was continuously recorded, and the position of the cross was adjusted manually by the operator. A calibration was made of the potentiometer output such that it directly indicated the position of the "foam height indicator". The indicator was continuously adjusted during the tests.

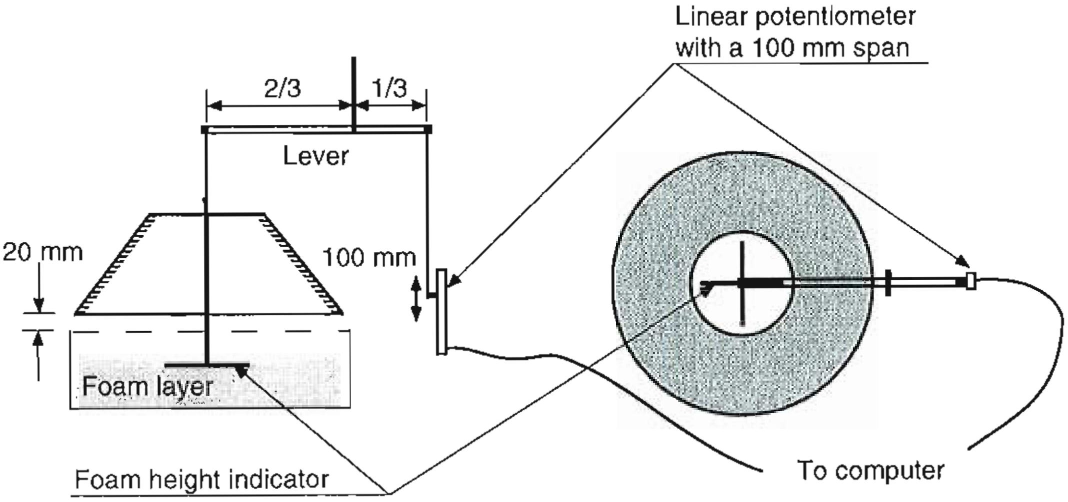


Figure 10 The foam height was measured by using a linear potentiometer connected to a "foam height indicator" which was continuously adjusted during the tests.

The radiation cone used was of the same type as is used in ISO 5657, the ISO ignitability test [7]. The cone used in the ISO 5660 method [8] (the cone calorimeter) has a higher heat output and would be preferable to use if a higher heat flux is desired. In these two "reaction-to-fire test" methods, the test sample is smaller, Ø = 155 mm in ISO 5657 and 100 x 100 mm in ISO 5660-1, as compared to the diameter of the pans used in these tests, Ø = 230 mm. The various radiation levels used in the test series were achieved by controlling the input voltage to the cone.

In order to verify the test conditions, the centric radiative heat flux at different voltage levels and the radiative heat flux at various horizontal positions and heights below the cone at one specific voltage level were measured. The results of these measurements are presented in figure 11.

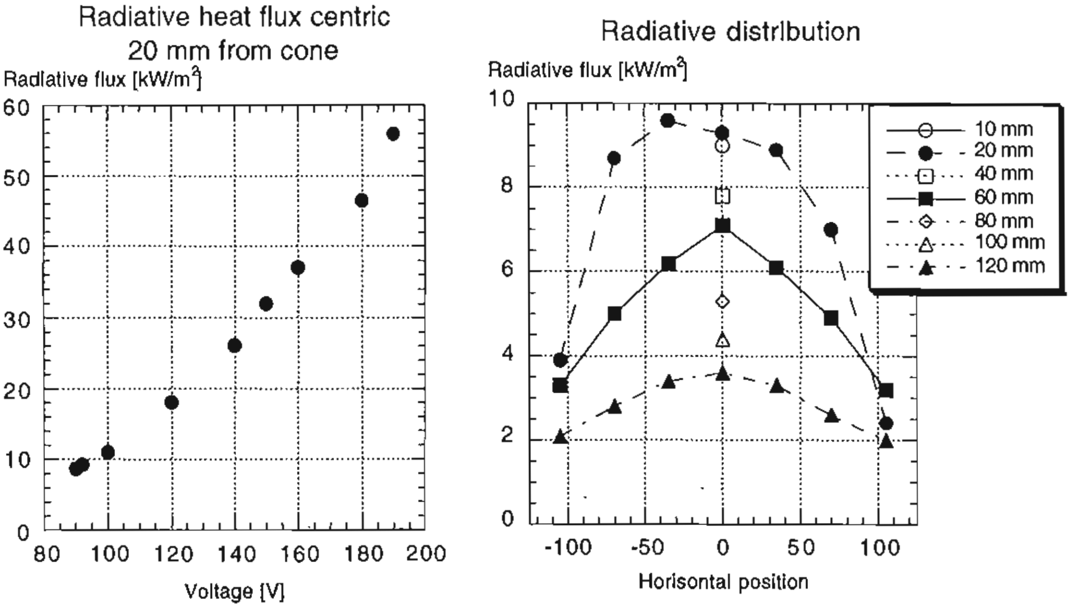
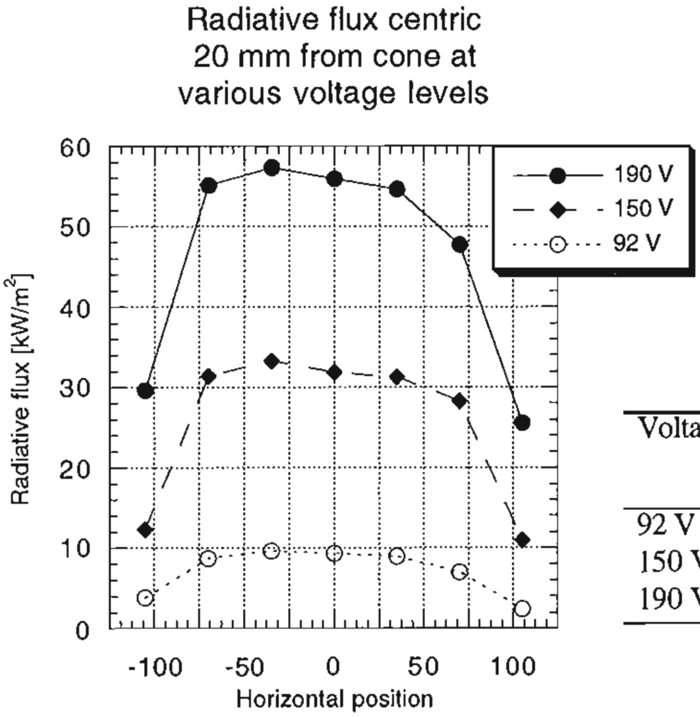


Figure 11 Radiative heat flux, 20 mm below the center of the cone at different voltage levels (left) and radiative heat flux at various horizontal positions and distances below the cone at a fixed voltage of 92 V (right).

The increased "target" size as compared to the reaction to fire tests mentioned above results in a more uneven distribution of the radiation at a given height, with a higher radiation in the centre and decreasing flux towards the edge of the vessel. According to ISO 5657 the radiation may deviate a maximum of 5% over the centric Ø = 100 mm circle. All tests were conducted using a fixed distance, 20 mm, between the cone and the vessel. By using this short distance it was possible to reach high radiative fluxes, which was desired in this project.

The radiative heat flux distribution, 20 mm below the cone, was measured for the three different voltage levels used, 92 V, 150 V and 190 V. The results are shown in figure 12. An average of the radiative flux across the entire surface, weighed by area, was calculated for the different voltage levels. The average value ("effective radiation") as compared to the peak value decreases from around 75% at 190 V down to around 65% at 92 V.



Voltage	Average ("effective") radiative flux
92 V	6,1k W/m^2
150 V	22,5 kW/m^2
190 V	42,6 kW/m^2

Figure 12 Radiative heat flux distribution and "effective radiation" towards the foam surface, 20 mm below the cone, at different voltage levels.

3.2 Test procedure

The steel pan was filled with a fixed amount of fuel (see table 1). The data logging system connected to the scale was started and the reading of the scale was tared to zero with the fuel in the pan. A cover with a circular hole, slightly smaller than the diameter than the pan, was placed on top of the pan to facilitate the removal of excess foam.

The foam was generated from a premix solution with the UNI 86R nozzle and the foam stream was directed onto a slider. The foam was collected in a plastic container (approx. 10 l volume) with a side opening 15 mm above the bottom level. The steel pan was then filled with foam from the container 1 minute 20 seconds after start of the data logging system. Excess foam was removed, level with the rim of the pan, and the cover was removed. The expansion ratio was then calculated from the initial foam weight. A radiation shield, which separated the cone from the pan during the filling procedure, was removed and the cone was turned 180° to a position centric above the pan at 2 minute 20 seconds. The foam height indicator was adjusted to the foam height. The when the first drainage could be seen was recorded as well as the continuos drainage every 2,5 - 10 ml depending on which pan and measuring cylinder was used.

At the end of the test, the fuel was ignited by a pilot propane flame or the cone itself. The height measuring system was moved all the way up and the flames were extinguished by a board placed over the pan.

3.3 Results from heat exposure tests

Including pre-tests, about 100 heat exposure tests have been conducted where foam types, foam thickness and radiation level were varied. Duplicate tests were conducted for all test conditions. The same three types of foam concentrate were used as described in chapter 2.2. An overview of all the tests is presented in table 3.

Table 3 Duplicate tests were conducted using three types of foam, three foam thickness and four radiation levels. The table indicate the test number for each test

Effective radiation (kW/m^2)	S	FP	AFFF/AR
	Test no - 25 mm foam thickness		
0	165, 166	118, 119	104, 105
6,1	159, 160	116, 117	106, 107
22,5	161, 162	114, 115	108, 109
42,6	163, 164	112, 113	110, 111
	Test no - 50 mm foam thickness		
0	151, 152	121, 122	88, 89
6,1	149, 150	123, 124	157, 158
22,5	147, 148	125, 126	155, 156
42,6	145, 146	127, 128	153, 154
	Test no - 100 mm foam thickness		
0	137, 138	135, 136	96, 97
6,1	139, 140	133, 134	98, 99
22,5	141, 142	131, 132	100, 101
42,6	143, 144	129, 130	102, 103

Some general observations made during the tests were that :

- the upper layer of the foam expands when exposed to radiation,
- the expansion finds an equilibrium state during several minutes where the continuos "heat" expansion of foam is balanced by the destruction of foam by the radiation,
- during the periods with the highest drainage rate, the readings are based on judgements because of the unclear interface between drainage and fuel,
- before established flames were formed, several flashes occurred with shorter and shorter increments until sustained flaming was reached,
- the first drops of drained foam solution was normally observed about half a minute after start of heat exposure.

In figure 13 - 15, some of the data from the test series are shown as examples. The time scale used in the figures is referring to the start of the data logging equipment which means that the heat exposure started at 2 minutes 20 seconds as indicated in the graphs. The results shown is the test data using the AFFF/AR at no radiation (0 kW/m^2) and at 22,5 kW/m^2.

In figure 13, the drainage measurements are shown. The upper graphs show the recorded drainage in ml, the middle graphs the same figures converted to percentage and the lower graphs show the drainage rate calculated per square meter. The graphs, which show the results for both tests conducted at each condition, indicate a very good repeatability.

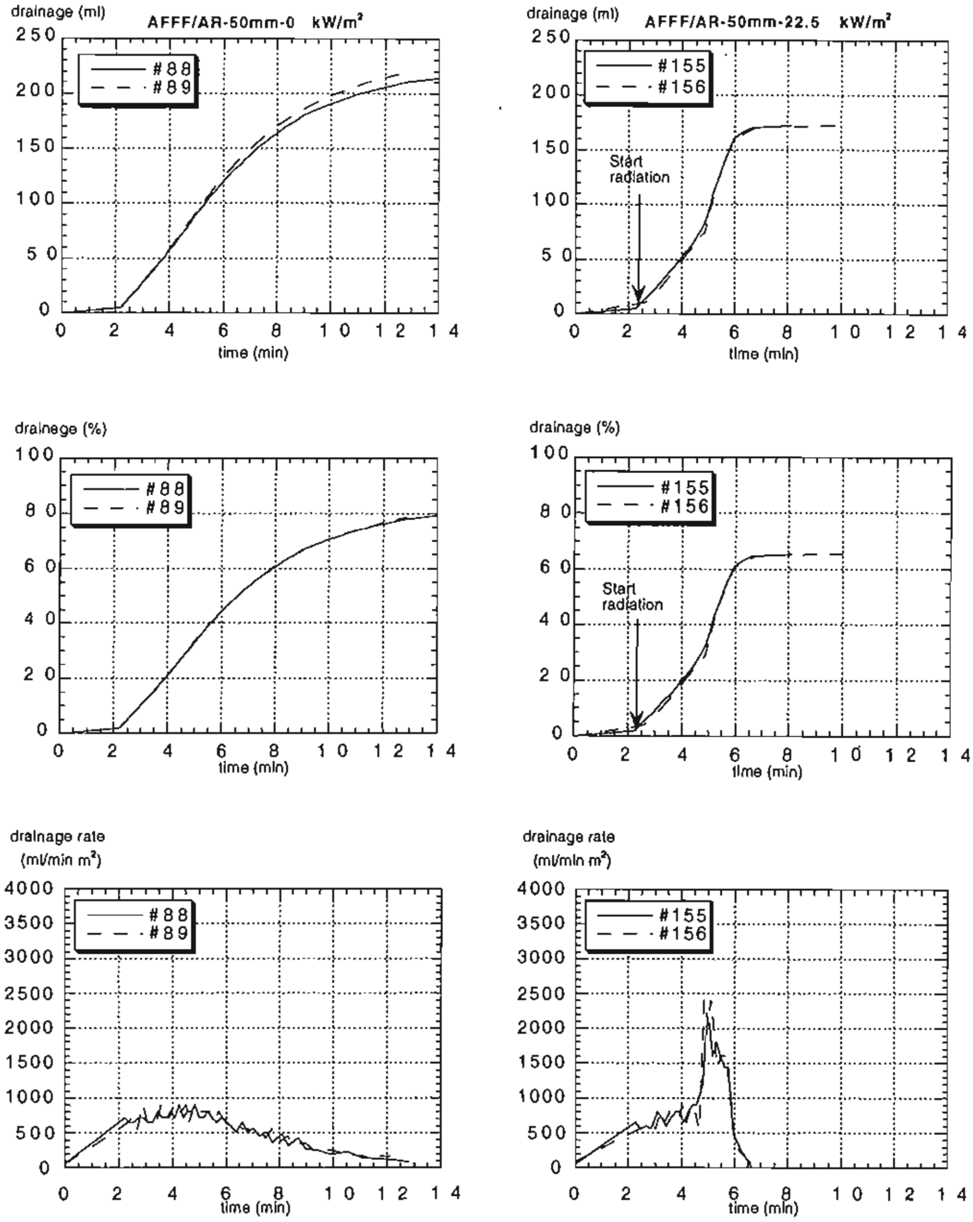


Figure 13 Drainage data shown as an example from the tests with AFFF/AR at no radiation (0 kW/m^2) and 22,5 kW/m^2. As shown in the graphs, the repeatability was very good.

In figure 14, the evaporation and evaporation rate is shown from the AFFF/AR at 22,5 kW/m^2. The evaporation rate is calculated per square meter. The disturbances in the beginning and at the end in the graphs is related to the filling of the vessel and the extinction of the fire after the test. Also here the heat exposure starts at 2 minutes 20 seconds.

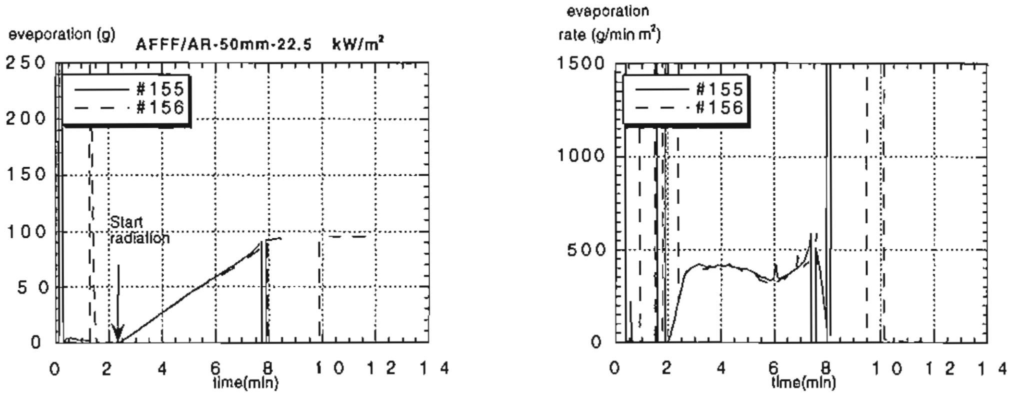


Figure 14 Evaporation data shown as an example from the tests with AFFF/AR at 22.5 kW/m².

Figure 15 shows the foam destruction and foam destruction rate for the AFFF/AR at 22,5 kW/m². The heat exposure starts at 2 minutes 20 seconds and the disturbances before that time, are related to adjustments of the height indicator when the cone is turned into position. The rim of the pan is in these tests approximately equal to 1,4 cm and as can be seen in the left graph, the foam layer expands very quickly, in this test approximately 1 cm, when exposed to the heat. The foam destruction then proceeds until the fuel surface ignites, which is indicated by the foam height indicator being raised very quickly. Since the fuel layer is increasing slowly during the test due to drainage and the foam layer is not completely even, there are some uncertainties and the values should not be considered as absolute. However, the calculated foam destruction rate which is based on the relative changes during the tests, is not considerably influenced by these uncertainties.

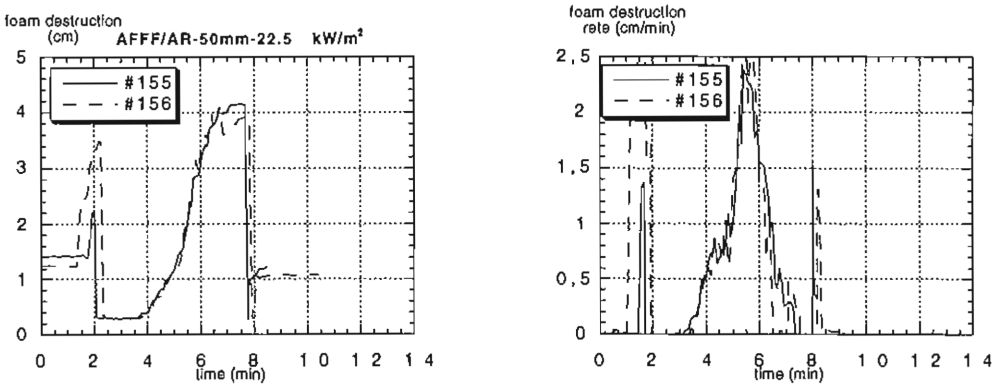


Figure 15 Foam destruction data shown as an example from the tests with AFFF/AR at 22.5 kW/m².

A summary of all test data for each foam is shown in figures 16 - 18. Here the peak drainage rate, peak evaporation rate and peak foam destruction rate have been plotted as a function of the initial foam layer thickness. As shown in the figures, both the drainage rate and foam destruction rate are considerably affected both by the heat radiation and foam thickness. The evaporation rate is almost linear to the radiative flux and independent of the foam thickness.

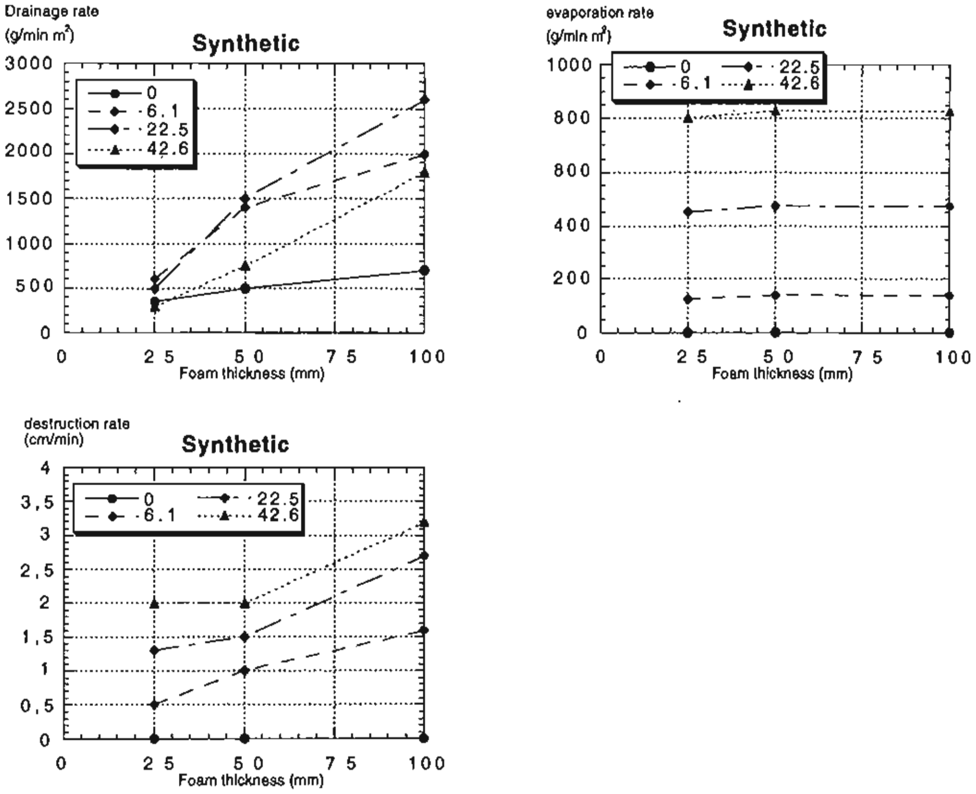


Figure 16 Peak drainage rate, evaporation rate and foam destruction rate at various heat flux rates as a function of foam thickness for the synthetic foam.

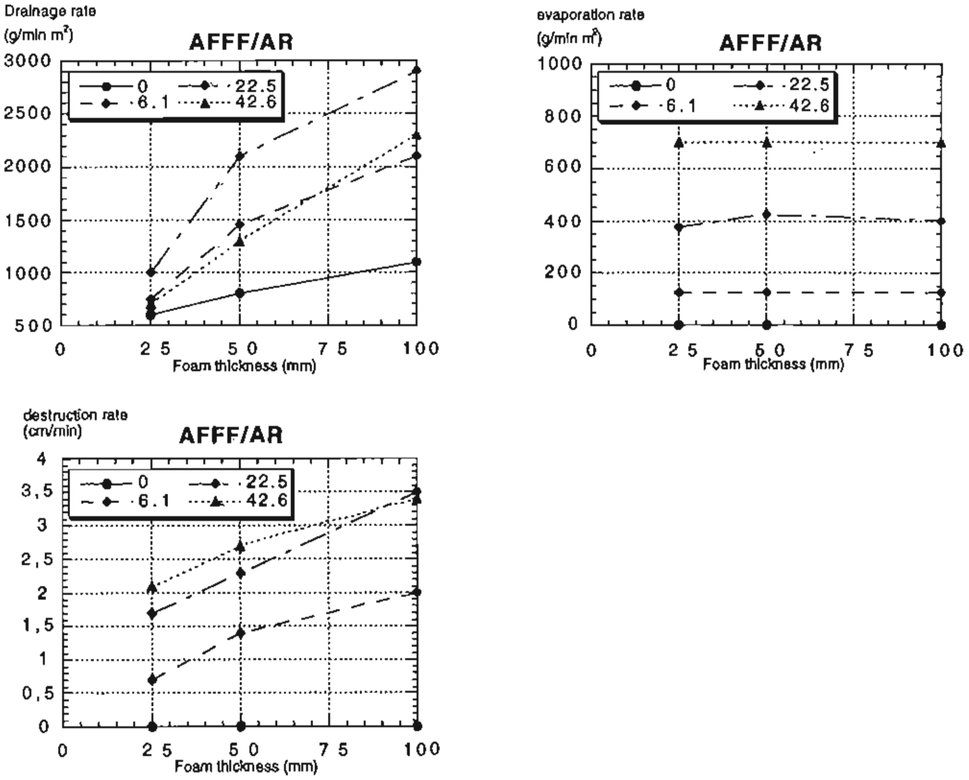


Figure 17 Peak drainage rate, evaporation rate and foam destruction rate at various heat flux rates as a function of foam thickness for the AFFF/AR foam.

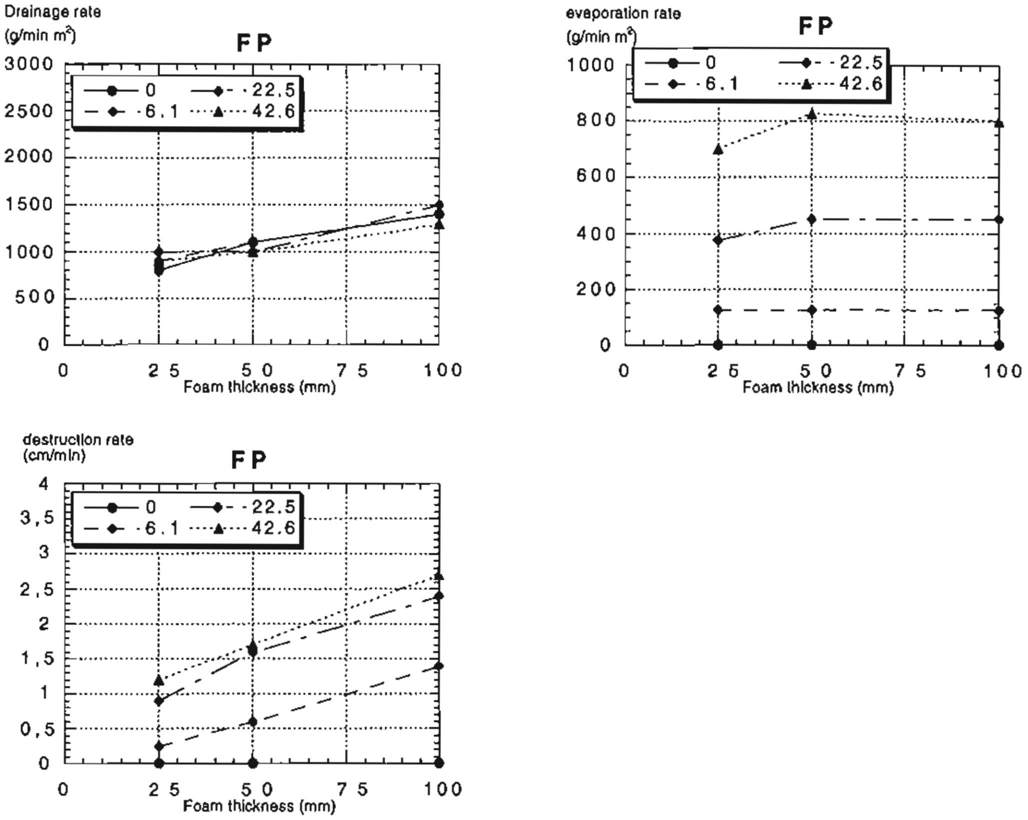


Figure 18 Peak drainage rate, evaporation rate and foam destruction rate at various heat flux rates as a function of foam thickness for the fluoroprotein foam.

In the heat exposure tests, time to ignition of the heptane surface was recorded. In figure 19, these ignition times are plotted as functions of the foam thickness for the three tested foams and the three heat fluxes. As shown in the graphs, the repeatability is very good. There is also a considerable difference between the foams at the lowest heat flux (6,1 kW/m^2). As expected the FP foam gave the longest time to ignition. When the heat flux is increased, the time to ignition decreases and the difference between the foams becomes marginal. The difference in ignition time between 22,5 kW/m^2 and 42,6 kW/m^2 is also small.

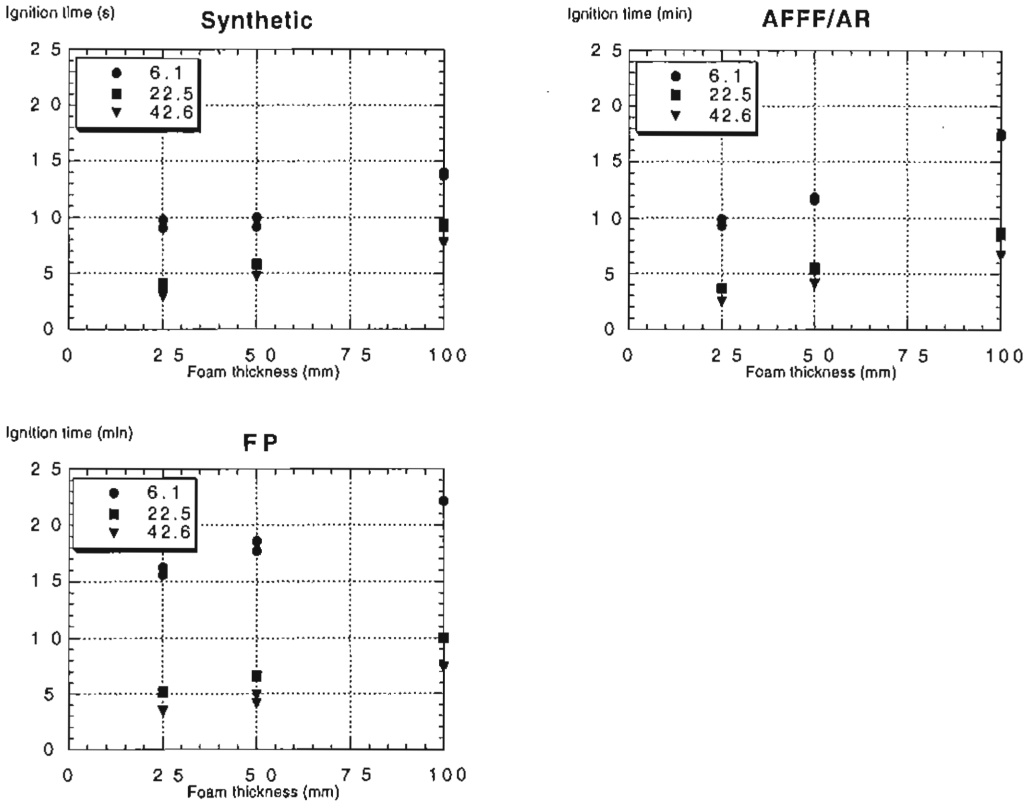


Figure 19 Summary of time to ignition at various heat flux rates as a function of foam thickness for the three tested foams.

4 Tests with temperature measurements

A series of tests with temperature measurements in the fuel and in the foam layer was conducted using the stainless steel pan with side drain for 50 mm foam layer depth and a radiative flux of 22,5 kW/m^2. Two foams, the synthetic and the FP were examined.

The stainless steel pans with side drain was chosen for these tests in order to have a constant height of the interface between the liquid and the foam layer. The repeatability of the drainage rate in the previous tests was so good that the drainage rate was assumed to be similar in these tests and therefore no measurements were made. Since the density of diesel is lower than the density of water, the drained foam-water solution will sink to the bottom of the pan and the drainage that overflows consists virtually of fuel only.

A rough measure of the evaporation rate was obtained by manual recording of the scale reading every 60 seconds. The destruction rate was recorded by using the height indicator that has been described earlier.

4.1 Test set-up

The stainless steel pan with side drain is shown in figure 7 and the test set-up in figure 20. The thermocouples were shielded type K elements with an outer diameter of 0,25 mm. The thermocouples were positioned with 10 mm interval as shown in figure 21.

The surface tension was no problem in these tests since the drainage was collected on the same scale as the pan with foam. The evaporation rate was continuously recorded by monitoring the scale.

In order to have less evaporation from the heated fuel, light diesel oil was used as fuel bed. Tests were performed with the fuel conditioned to 20 °C and 50 °C.

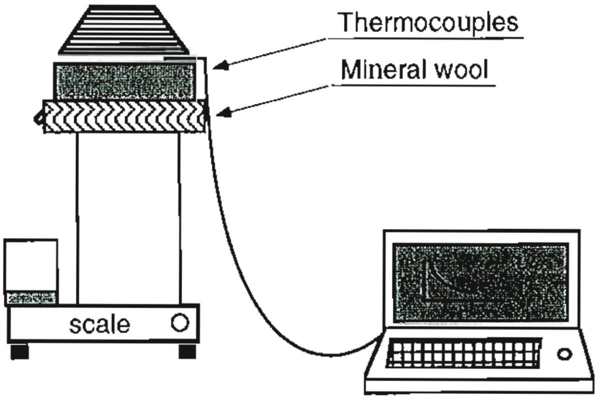


Figure 20 Test set-up for steel pans with side drain used in the temperature measurements. The portion of the pan that was in contact with the fuel was insulated with mineral wool.

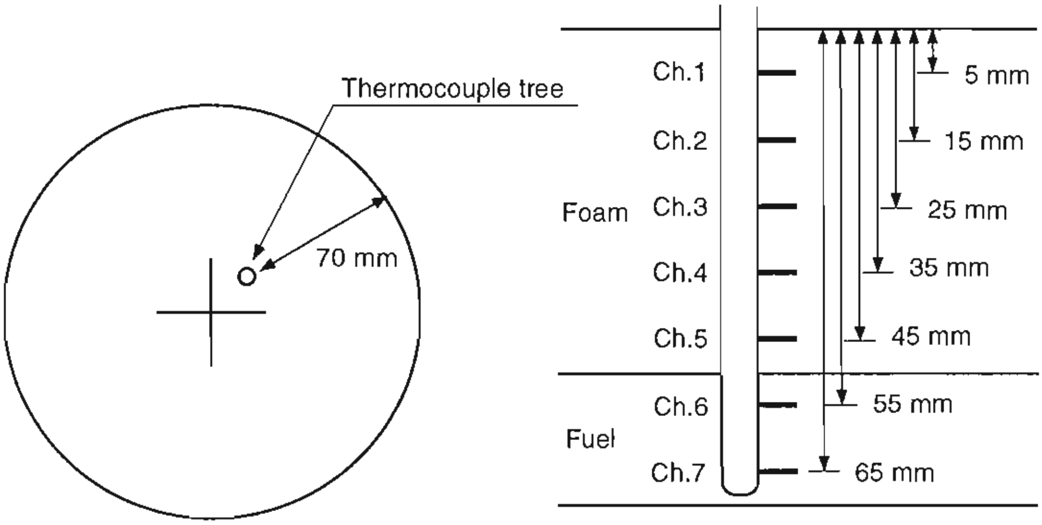


Figure 21 Positions of the thermocouples in the test pan

4.2 Results

The intention of the tests with temperature measurements was to get an idea of the heat balance in the foam-fuel system during heat exposure.

The thermocouples in the foam layer show that there is a heat wave penetrating some centimetres into the foam layer. This can be seen in the graph in figure 22.

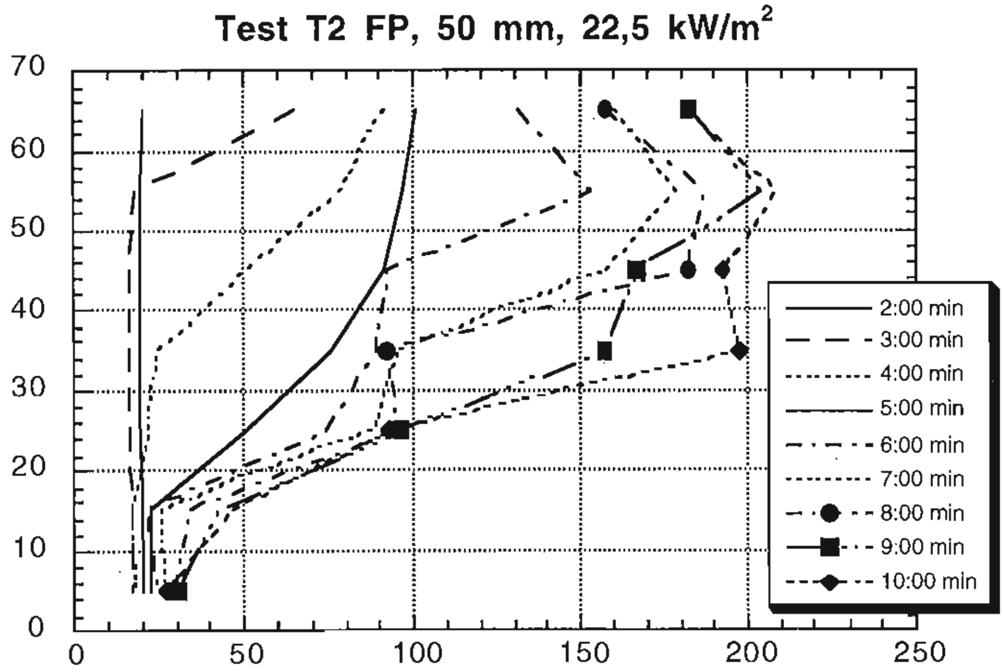


Figure 22 Heat wave through the foam-fuel system in test T2, with the FP foam at 20°C fuel temperature. Heat exposure starts at 2 minutes 20 seconds.

In the liquid, the lowest thermocouple shows a stepwise increase in temperature after around 5 - 6 minutes in the tests with FP foam as shown in figure 23. The same behaviour can be seen in tests with both 20 °C and 50 °C fuel temperature. The temperature increase in thermocouple ch 6 is slightly delayed as compared with ch 7 but later in the test the temperature recorded is higher in ch 6 than in ch 7.

In the tests with synthetic foam both thermocouples show gradually increasing temperatures.

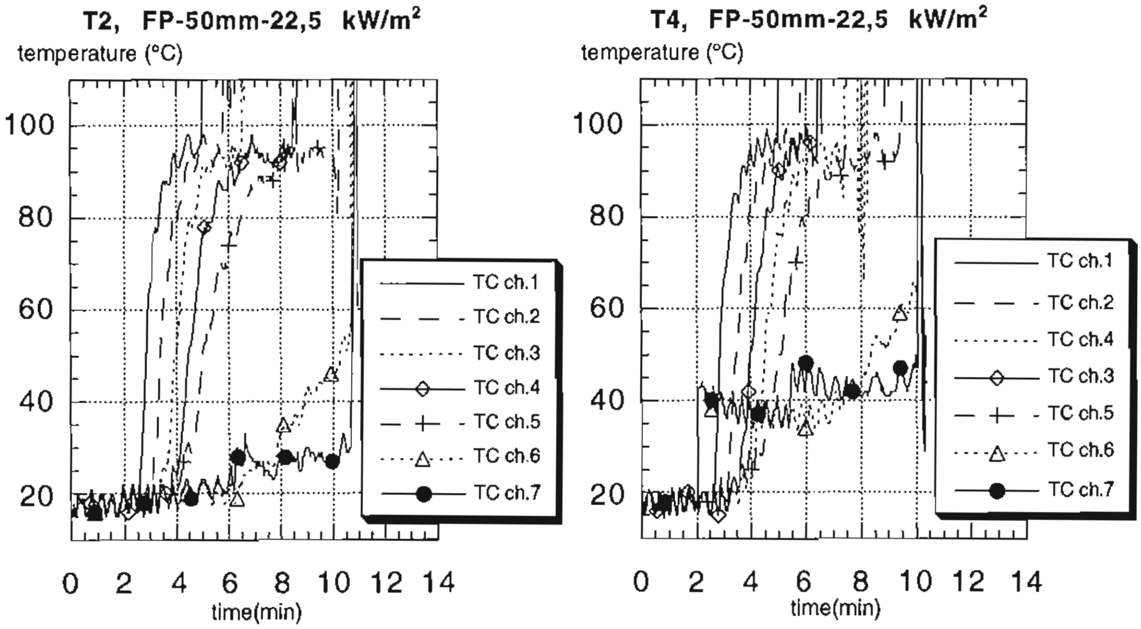


Figure 23 Thermocouple readings shown as examples from test T2 with the FP foam and the fuel at 20°C and test T4 with the FP foam and 50°C fuel temperature.

A simplified heat balance is shown in figure 24. The positive side of the energy balance consists mainly of the heat flux from the cone. On the loss side, energy is stored in the liquid, in the foam and in the pan and is lost due to evaporation of foam, heated overflowing fuel and heat reflected, convected or conducted away from the system.

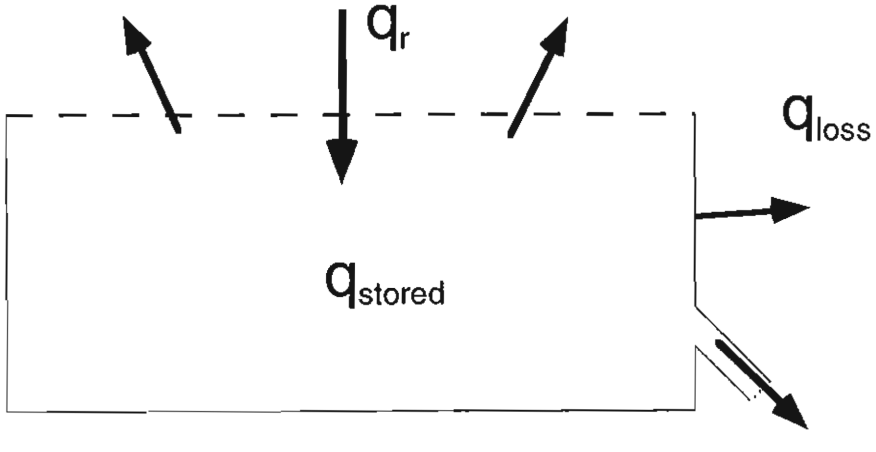


Figure 24 Principal diagram showing the energy balance of the pan during heat exposure.

The heat balance can be checked either at a specific time step during the test or as a lumped heat balance with the whole test period as the time frame. In the example below, the heat balance for test T2, with FP foam is calculated for the whole test period.

The radiative energy in test T2 until ignition is 22,5 kW/m^2 x 0,0415 m^2 x 488 seconds, which gives approximately 450 kJ.

The temperature in the overflowing fuel was not measured. The energy in this fuel has therefore been estimated based on the readings of channels 5, 6 and 7.

The energy in the remaining fuel and drainage has been calculated based on the readings of channels 6 and 7. It is assumed that they are each representative of one half of the liquid volume and that the drainage enters the lower volume at a rate according to the measurements in test #125 and #126.

The energy stored in the part of the pan not in contact with the fuel has been estimated based on the black body temperature assuming a radiative flux of 5 kW/m^2 and an absorbency of 70 - 90%. This corresponds well with thermocouple readings above the fuel of 180 - 215 °C. For the parts of the pan in contact with the fuel, the reading of thermocouple channel 7 was used for the estimate.

The energy stored in the foam can be neglected after ignition since there is no foam left.

In test T2, 127 grams of foam evaporated. If heat capacity and heat of vaporisation is assumed equal to water, this corresponds to 330 kJ, around 75% of the heat input. The energy in the overflowing fuel has been estimated to 1 - 6 kJ. The energy in the remaining fuel and drainage, to 27 - 30 kJ. This corresponds to a total of 5 - 8% of the energy being absorbed by the drained foam. The energy stored in the pan was 30 - 35 kJ, which also equals 5 - 8% of the energy. We can thereby account for 385 - 400 kJ, corresponding to 85 - 90% of the energy from the cone.

5 Discussion and conclusions

The aim of the project was to improve the measurement technique for drainage and foam destruction rate compared to the previous investigation reported in SP-Report 1992:54 [1]. The influence of foam layer thickness was also to be investigated as well as the energy balance in the foam-fuel system during heat exposure.

Initially, it was proposed to conduct further tests using thicker foam layers than in the previous study [1]. However, experimental and modelling work on foam flow [9,10], has shown that the foam layer thickness is in the range of 2-5 cm during the initial foam spread on a liquid surface. Based on this, foam thicknesses of 25 mm, 50 mm and 100 mm were chosen for this study.

The drainage rate measurement procedure has been improved to achieve a good resolution of the drainage rate as a function of time. The method is based on the use of a measuring cylinder beneath the test pan where the interface between the fuel and the foam solution is recorded visually. The methodology described in NT FIRE 023, Part 2, using an overflow arrangement on the side of the test pan, was not possible to apply, as fluctuations in the drainage onset and drainage rate occurred due to surface tension effects.

The height measurement technique have also been improved making it possible to get an on-line measurement of the foam layer thickness and thereby a better possibility to determine the foam destruction rate as a function of time.

5.1 Evaporation and heat balance

The heat balance in the foam-fuel system has been studied further. Both the tests in the previous project [1] and in this project show that the evaporation is almost linear with the heat radiation. An "evaporation constant" of about 15 g/min kW was calculated in the previous project, which could be compared with the maximum theoretical value, 23,1 g/min kW. One question raised from these figures was, how much of the remaining energy is absorbed by the foam and drained foam solution and how much is reflected from the foam surface.

Temperature measurements have therefore been conducted in the foam, fuel and drained solution. A more careful examination of the radiative heat flux pattern towards the exposed foam layer has also been made. The latter shows that the heat flux differs over the pan surface. The "effective radiation" is therefore considerably lower than the peak radiation measured below the center of the radiation cone. For the radiation heat fluxes used in this project, the effective radiation is about 65 - 75% of the center value. Based on this, the effective radiation levels used in this project have been calculated to 42,6, 22,5 and 6,1 kW/m^2. The effective radiation levels and the evaporation rate measurements, indicate an evaporation constant of 18,2 g/min kW for the AFFF/AR, 19,2 g/min kW for the FP and 20.7 g/min kW for the synthetic foam. The relative relation between the evaporation constants for the three types of foam are the same as in the previous investigation [1], where the evaporation constant varied between 13,5 and 17,0 g/min kW. The radiation figures from the previous tests can be converted to effective radiation using the same correction factor as in this project, the radiation would then be reduced to about 70% of the peak radiation. This means that the reported evaporation constant was to low and should be about 21,5 g/min kW (15 g/min kW / 0,7). There are still uncertainties in these figures as the effective radiation is referred to the initial distance (20 mm) between the foam layer and the radiation cone. As the foam expands, the heat flux towards the upper layer increases, resulting in a slightly lower evaporation constant. Considering these uncertainties and the differences between various foams and test conditions it is reasonable to assume an average evaporation constant of 18 - 21 g/min kW, i.e. that 80% - 90% of the energy is used for the evaporation of the foam.

The temperature measurements in the foam-fuel system indicate that about 25 - 35 kJ is absorbed by the foam which corresponds to approx. 5 - 8% of the total energy input. This is based on the total temperature increase of the fuel layer, the drained foam solution and the test pan from start of radiation until all the foam is destroyed and ignition occurs.

5.2 Drainage characteristics

The results show that the drainage characteristics are dependent both on foam thickness and radiative heat flux. The drainage rate increases considerably already at low radiation for the synthetic and AFFF/AR foam while the FP foam is hardly influenced at all. Increasing foam thickness also increases the drainage rate. The maximum drainage rate was reached at the effective radiation of 22,5 kW/m^2 while it was reduced again at the highest radiation. This is probably due to the increasing evaporation which "gives less time" for the foam to drain. This is also shown by the fact that the total drainage from the foam decreases by increasing radiation and decreasing foam thickness as shown in figure 25. Extrapolation indicates that the drainage from the "foam front" during extinguishment is probably almost zero and all the foam is evaporating.

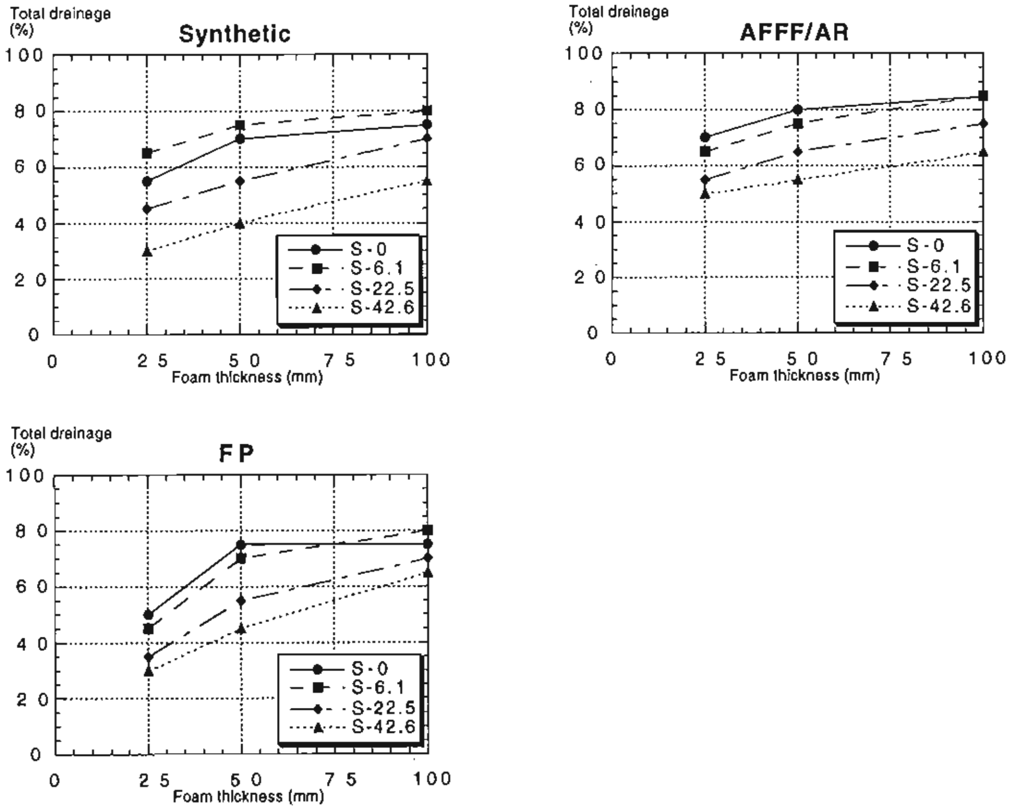


Figure 25 The total drainage from the foam layer decreases with increasing radiation and decreasing foam thickness.

5.3 Foam destruction and time to ignition

When a foam is exposed to heat radiation, there is initially an expansion of the upper part of the foam layer due to expansion of the foam bubbles. After some time delay, these bubbles starts to break down and the next layer starts to expand, etc. After some time period, the foam destruction increases and a high destruction rate is achieved. When the foam is consumed the fuel ignites. Because of this initial foam expansion period, there is a considerable difference in peak foam destruction rate and "effective foam destruction rate", defined as the initial foam thickness divided by the time to ignition. As shown in figure 26, the peak destruction rate for the AFFF/AR was about 3,5 cm/min while the effective destruction rate was only 1,5 cm using a foam thickness of 100 mm.

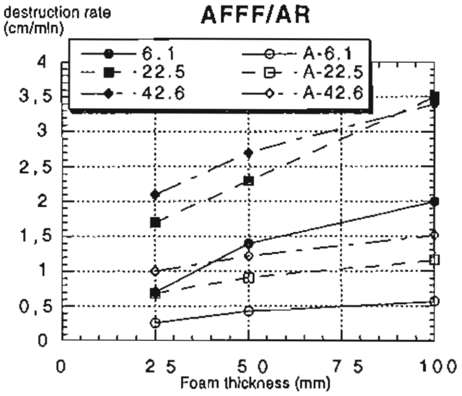


Figure 26 Maximum (solid symbols) and "effective" foam destruction rate (open symbols) for the tested AFFF/AR at various radiation levels and as a function of foam thickness.

Time to ignition is effected by the type of foam mainly at lower radiative heat fluxes. At the effective radiation level of 6,1 kW/m^2, the FP foam is giving a considerably longer time to ignition compared to the synthetic foam as shown in figure 27. When the radiation increases, the time to ignition decreases and the difference between the foams becomes marginal which verifies the tendency seen in the previous investigation [1].

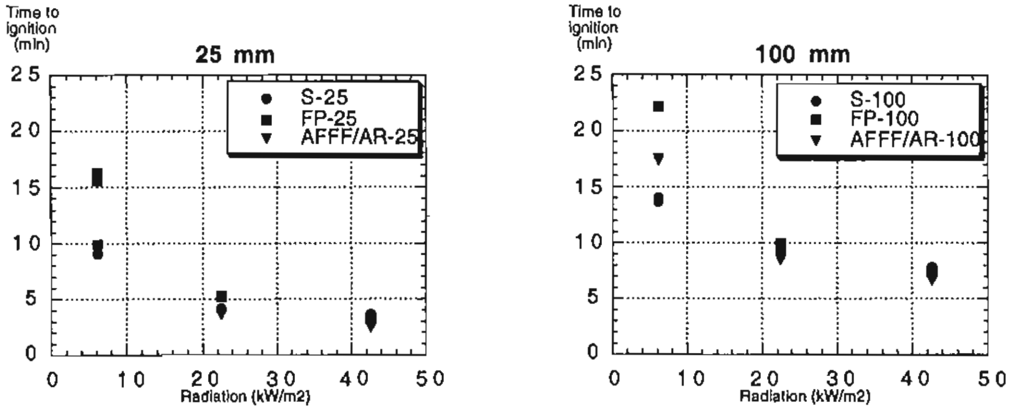


Figure 27 Time to ignition as a function of effective radiation towards the foam surface using an initial foam thickness of 25 mm and 100 mm, respectively

Comparing the ignition times achieved using 100 mm foam thickness at 6,1 kW/m^2 with time to 25% burn back during standard scale fire tests with the same foam concentrates in the FAIRFIRE project [5] indicates a relative good correlation. As shown in figure 28, the time to 25% burn back is only slightly longer than time to ignition and the correlation seems linear for all three foams.

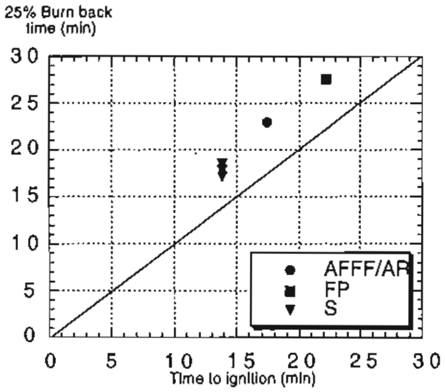


Figure 28 Comparison between 25% burn back in 4,5 m^2 fire tests [5] and time to ignition during heat exposure tests at 6,1 kW/m^2 and an initial foam thickness of 100 mm.

The tests show that a considerable amount of information on the behaviour of foam during heat exposure can be obtained by the test method used. The repeatability is very good and the method is relatively simple and fast to use. Certain improvements of the equipment is still possible, e.g. automatic registration the drainage and a refined device for the foam thickness measurements.

The test method does not on its own provide the information why certain foams are more efficient than others. The most obvious correlation with normal fire tests is the burn back behaviour. For a full understanding of the extinguishing properties, other factors must also be considered, such as flow properties and resistance against the fuel during forceful application. The method might however provide a part of the information needed e.g. as input in modelling work.

6 References

[1] Persson, H.,"Fire Extinguishing Foams - Resistance Against Heat Radiation", SP Report 1992:54, Borås 1992

[2] ISO 7203-1, "Fire extinguishing media-Foam concentrates-Part 1: Specification for low expansion foam concentrates for top application to water-immiscible liquids", First edition 1995-12-15

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[9] Dahlberg, M., "Foam Spread Experiments on a Water Surface", SP Report 1994:16, Borås 1994

[10] Persson, B., Dahlberg, M., "A Simple Model of Foam Spreading on Liquid Surfaces", SP Report 1994:27, Borås 1994

Annex 1-Test method

Introduction

When a burning liquid is extinguished with fire fighting foams, there are several factors which influence the extinction. Detailed studies of the various factors involved in the extinguishing process are needed to get a better understanding of the extinction mechanisms.

The capability of fire fighting foams to resist heat radiation is one such factor which is of great importance. This method describes equipment and a procedure which is possible to use for the characterisation of foams during heat exposure.

Scope and field of application

This method is primarily intended for research work rather than commercial testing and the method should therefore be used as guidance. It has been developed and used in two research projects [A1, A2] providing further information which could be of interest for the user.

The method is focusing on the behaviour of foams during heat exposure and provides data and characteristics about the drainage rate, evaporation rate and foam destruction rate. It also provides data which is similar to the 25% burn back time normally achieved in standardised fire tests.

It is important to note that the test method does not on its own provide the information why certain foams are more efficient than others. For a full understanding of the extinguishing properties, other factors must also be considered, such as flow properties and resistance against the fuel during forceful application. The test method might however provide a part of the information needed e.g. as input in modelling work.

References

[A1] Isaksson, S., Persson, H.,"Fire Extinguishing Foams - Test method for heat exposure characterisation", SP Report 1997:09, Borås 1997

[A2] Persson, H.,"Fire Extinguishing Foams - Resistance Against Heat Radiation", SP Report 1992:54, Borås 1992

[A3] ISO 7203-1, "Fire extinguishing media-Foam concentrates-Part 1: Specification for low expansion foam concentrates for top application to water-immiscible liquids", First edition 1995-12-15

[A4] DRAFT prEN 1568-3, "Fire extinguishing media-Foam concentrates-Part 3: Specification for low expansion foam concentrates for surface application to water-immiscible liquids, August 1994

[A5] ISO 5660-1, "Fire tests-Reaction to fire-Part 1: Rate of heat release from building products (Cone calorimeter method)", First edition 1993-06-01

Definitions

Drainage rate: Drainage in gram per minute and square meter foam surface

Effective foam destruction rate: Initial foam thickness divided by the time from start of heat exposure until sustained flaming (cm/min)

Effective irradiance: Average of the irradiance, weighed by area, across the entire surface

Evaporation constant: Evaporation in gram per minute and square meter foam surface divided with the effective irradiance (g/min kW)

Evaporation rate: Evaporation in gram per minute and square meter foam surface

Flashing: Existence of flame for periods of less than 1 s, on or above the fuel surface initially covered with foam.

Foam destruction rate: Foam destruction in cm per minute measure in the center of the test pan

Irradiance: The radiant flux incident per unit area on an infinitesimal element of surface.

Sustained flaming: Existence of flame on or above the fuel surface initially covered with foam for periods of over 4 s.

Transitory flaming: Existence of flame on or over the fuel surface initially covered with foam for periods of between 1 and 4 s.

Test principles

A stainless steel vessel with bottom drain is used for the heat exposure tests. The vessel is placed on a scale connected to a data logging system in order to record the weight loss and thereby the evaporation rate, see figure A1.

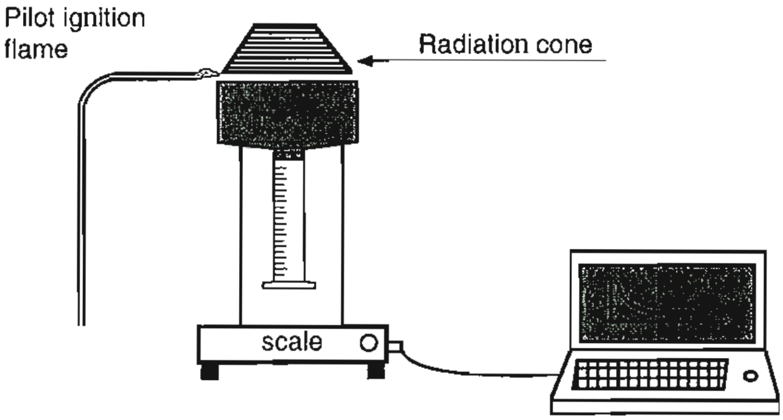

Figure A1 The test pan is placed on a scale connected to a data logging system in order to record the evaporation rate. The drainage is measured with a measuring cylinder connected to the test pan

The radiation cone is supported on a separate stand, positioned with its lower rim 20 mm from the rim of the test pan. During the test, the foam layer will be destroyed such that fuel vapours will be released. These is ignited by a small propane pilot flame, positioned at the rim of the pan.

The foam solution-fuel interface is determined visually in the measuring cylinder.

A "foam height indicator" connected to a data logging system is used to record the foam level during the test.

Test equipment

Foam generation

Foam is preferably generated with a test nozzle, e.g. the UNI 86 used in the ISO 7203-1 and prEN 1568-3 standards [A3, A4] or the small scale version of this nozzle, UNI 86R. Other equipment specified in these standards are also useful such as premix tanks and a foam slider for foam collection.

A plastic container of approximately 10 l volume is used for initial foam sampling. The container should have an opening, about 50 mm wide and 100 mm high, on its side, 15 mm from the bottom. A thin plastic sheet, placed on the inside of the container is used to cover the opening during foam sampling.

Test pan

Different test pan/measuring cylinder combinations for various foam layer thickness can be used, see table A1. The bottom of the pan shall have a slope of 10° towards the bottom outlet. On the outside of the outlet two grooves are made to hold O-rings for fixing a standard measuring cylinder to the pan, see figure A2.

(Note: The test pan proposed is slightly smaller than the size used in the development tests. This is to achieve a more uniform irradiance, also near the rim of the pan)

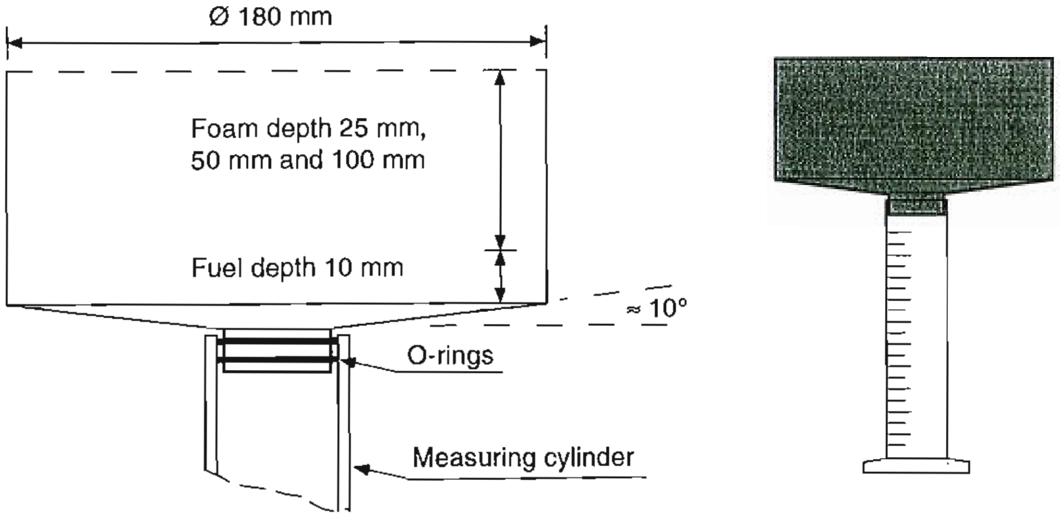

Figure A2 Suitable design of test pan for the heat exposure tests, equipped with a measuring cylinder.

The vessel is filled with fuel such that the fuel depth along the rim is 10 mm. (Water-miscible fuels makes it impossible to measure the drainage rate).

Table A1 Suitable combinations of test pans and measuring cylinders

Foam depth [mm]	Measuring cylinder size
25	100
50	250
100	500

Foam height measuring device

A "foam height indicator" is used to record the foam height during the test, see figure A3. A linear potentiometer is connected via a lever to the height indicator (a horizontal cross made from thin steel wire). The signal from the potentiometer is continuously recorded by a data logging system, and the position of the indicator is adjusted manually by the operator. The height indicator and the potentiometer shall be calibrated such that the output directly indicates the position in relation to the rim of the test pan.

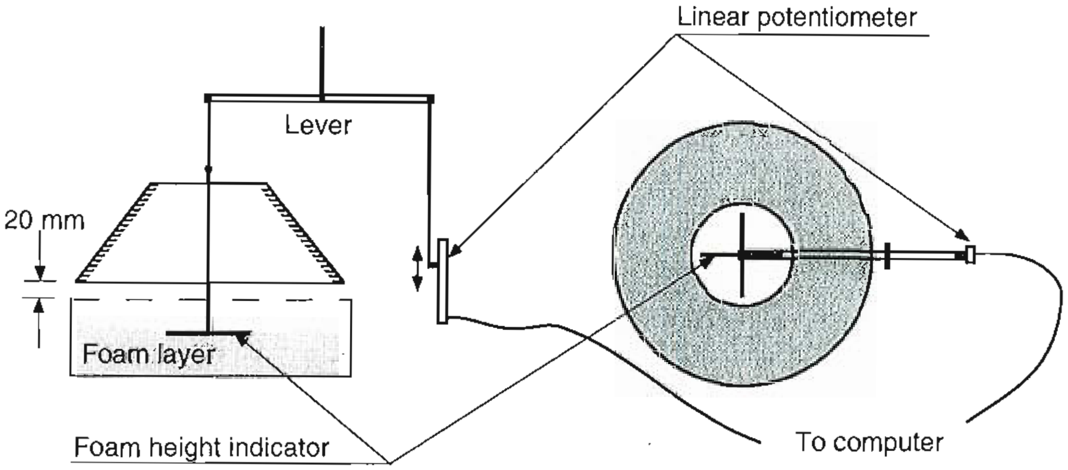

Figure A3 The foam height is measured by using a linear potentiometer connected to a "foam height indicator" which is continuously adjusted during the test.

Radiant electrical heater

A cone-shaped radiant electrical heater should be used to generate the heat exposure. A suitable device is described in clause 6.2 of the cone calorimeter standard, ISO 5660-1 [A5].

The heater should be mounted on a stand such that the position of the lower rim of the cone is 20 mm above the rim of the test pan. The cone should also be possible to turn 180° away from the test pan to a "stand-by position" during foam filling procedure, etc. A shield between the cone in its stand-by position and the test pan is also recommended.

The irradiance towards the foam surface is controlled by a temperature controller described in clause 6.3 of ISO 5660-1.

In order to determine the effective irradiance, the irradiance distribution, 20 mm below the cone, and along the diameter of the test pan should be recorded. The effective radiation is then calculated as an average of the measured irradiance, weighed by area.

Weighing equipment

The test pan should be placed on a scale or a load cell equipment connected to a data logging system. The accuracy should be ±0,5 g or better.

Testing

The radiant heater is started and the temperature controller set to the desired temperature. Adjust the foam height indicator so that it is level with the rim of the test pan. Ignite the propane pilot flame and adjust the flame length to 15±5 mm.

A premix solution is prepared and the quality is checked by expansion and drainage measurements as described in e.g. ISO 7203-1.

The steel pan is filled with a fixed amount of fuel to achieve a 10 mm fuel depth along the rim. The data logging system connected to the scale is started and the scale is tared to zero. A cover with a circular hole, slightly smaller than the diameter than the pan, is placed on top of the pan to facilitate the removal of excess foam.

The foam is generated from the premix solution with a suitable foam nozzle and the foam stream is directed onto the slider. The foam is collected in the plastic container.

The steel pan is then filled with foam from the container at a specified time (normally 1 minute - 1 minute 30 seconds) after start of the data logging system. Strike the foam level with the rim of the pan and remove the cover. Record the foam weight and calculate the expansion value.

Remove the radiation shield between the cone and the vessel and turn the cone 180° to a position centric above the pan at a specified time (normally 2 minutes - 2 minutes 30 seconds) after start of the data logging system. Put the pilot flame into position. (Note: The pilot flame is only needed at low irradiance levels, at higher levels the fuel vapours are ignited directly by the hot radiator without any problems).

Adjust the foam height indicator such that it indicates the height of the foam surface. Record the drainage visually by reading the time until the foam solution-fuel interface is reaching each graduation (5 - 10 ml depending on measuring cylinder).

Record time to flashing, transitory flaming and sustained flaming. When sustained flaming has occurred, extinguish the fire e.g. by placing a piece of non-combustible board over the pan.

Test report

The reported data is of course depending on the intended use. The basic information gained from a test is:

- drainage and drainage rate as a function of time,
- evaporation and evaporation rate as a function of time,
- foam destruction and foam destruction rate as a function of time,
- time to ignition and
- effective foam destruction rate.

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SP REPORT 1997:09
ISBN 91-7848-667-X
ISSN 0284-5172