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High Expansion Foam Systems for Inside Air - Literature Review and Fire Tests

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Abstract

High Expansion Foam Systems for inside air - literature review and fire tests

The aim of the project was to improve and compile knowledge about high expansion (HIEX) foam systems using inside air. The experimental part has been focused on fires in high rack storages.

The project was mainly divided in two parts. The first part was to collect and evaluate information about HIEX foam systems in general and for inside air systems in particular. As the second part of the project, a test series in reduced model scale was conducted with a HIEX foam system for inside air.

The information about HIEX foam systems for inside air is rather limited. Research from the 1960-70th is available about foam destruction caused by smoke and heat. References and tests show that pyrolysis gases are able to decrease foam production considerably. It has also been shown that low located fires, like pool fires, are easy to put out with HIEX foam. Present standards do not specify any design criteria for HIEX foam inside air systems.

Present standards do not specify any design criteria for HIEX inside air system and present foam standards, ISO 7203, EN 1568 etc., do not evaluate foam concentrates for the use in HIEX inside air applications.

In a high rack storage where the vertical fire spread is rapid it is very important that the HIEX foam system is activated in an early stage in order to control the fire before the fire spreads to surrounding racks. If the air temperature used for foam production is allowed to increase above approximately 300°C the foam production and foam build up in the test enclosure is limited.

The tests also show that ventilation of the protected area affect the foam generation. If the fire is under ventilated and pyrolysis products are generated the foam generation decreases even if the temperature at the generators is rather low. The size of the protected enclosure and the degree of ventilation is very important and has to be considered when designing a HIEX foam system using inside air.

The test results can be used to estimate how the investigated parameters should influence the results in full scale if the scale effects are considered.

Key words: High expansion foam, inside air, high rack storage

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Preface

This project has been financed by the Swedish Fire Research Board (Brandforsk). The aim of the project was to improve and compile knowledge about HIEX foam systems using inside air.

The author would like to thank Svenska SKUM AB for the contribution of the foam system used in the tests, and in particularly Mr Hans Johansson for valuable discussions and comments.

Sammanfattning

Syftet med projektet har varit att ta fram och sammanställa kunskaper för system med lättskum alstrat med rökbemängd luft. De praktiska försöken har koncentrerats på snabb brandspridning i pallställage.

Projektet innehåller en fas med litteratur- och erfarenhetssammanställning och en experimentell fas. Den experimentella delen utfördes i en nedskalad uppställning för att möjliggöra fler försök med olika förutsättningar till en rimlig kostnad. Brandbelastningen bestod av gods staplat i pallställage där brandspridningen i vertikalled blir mycket snabb.

Information om lättskum alstrat med rök är relativt begränsad. Forskning från 1960-70 talen finns tillgänglig om nedbrytning av skum med värme och rök. Referenser och försök visar att pyrolysgaser kan minska skumproduktionen avsevärt. Det framgår också av tidigare erfarenheter att skumsläckning av poolbränder på marknivå är väl prövat och är ofta överlägset andra metoder.

Nuvarande standards specificerar ej några designkriterier för lättskumssystem där rökbemängd luft används. Ej heller standards för skumkoncentrat (EN 1568, ISO 7203 etc.) tar hänsyn till skummets egenskaper för användning med rökbemängd luft.

Generellt kan man säga att resultaten av de utförda försöken tyder på att aktiveringskriterium och påföringshastighet är de två viktigaste parametrarna. Med en tillräckligt hög påföringshastighet som startar i ett tidigt skede säkerställer man att tillräcklig stighastighet erhålls. Då temperaturen på luften för skumproduktion tilläts överstiga ca 300°C minskade skumproduktionen och därmed skumuppbyggnaden avsevärt.

Försöken visar också att ventilationen påverkar skumuppbyggnaden. Försöken visar att ökad ventilation innebär bättre skumuppbyggnad. Om branden är underventilerad och pyrolysgaser bildas minskar skumproduktionen trots relativt låga temperaturer. Storleken på det skyddade utrymmet och graden av ventilation påverkar systemets förmåga att generera skum och måste beaktas vid dimensionering av lättskumsystem där skummet alstras med rökgaser.

Försöken utfördes i skala 1:3. Provresultaten bör dock kunna användas till att uppskatta hur de undersökta parametrarna påverkar resultat i full skala. Detta förutsätter att skalningseffekter beaktas.

1 Introduction

High expansion (HIEX) foam as an extinguishing media was developed in the 1950th by the "Safety in Mines research Establishment" for protection of mines [1]. Since this period the extinguishing media and the system design have been developed and HIEX foam is now used in a lot of different applications.

Basically there are two different principles or concepts to produce foam with a HIEX foam system.

One is the conventional HIEX foam system in which the foam is produced with fresh air, which is taken from outside the protected area. This requires that that the fire room is well ventilated in order to avoid a positive pressure. If the fire room have a positive pressure compared to the area outside the foam production will decrease dramatically.

The second principle is HIEX foam systems where the foam is produced with combustion gases from inside the protected area, i.e. inside air. Due to the fact that the foam production will be influenced by smoke, heat and steam this has to be considered. The foam is produced without any electrical power supply or turbine to the generator [1)]. The generators do not include any movable parts and they can be installed without any access to fresh air. The disadvantage is that one have to consider some decrease in foam generation. This decrease depends on the atmosphere in the protected area.

One problem with a conventional HIEX foam system is that the generators are rather complicated and have a fan connected to a power supply. This, and the fact that the generators have to be located with access to fresh air, gives limitations in system design.

Common applications where HIEX foam systems are used include machinery spaces on ships, mines and aircraft hangars. The use of HIEX foam systems in industrial applications is rather limited. In the 1980th there was some research [1] and interest about these applications. In later years the use in industrial applications has been of interest because of the rather new concept with inside air. Especially in Holland and Belgium there has been an increase of use, because of local authorities rules that benefits the use of HIEX foam. The rather small amount of water used in HIEX foam systems, compared to sprinkler systems, reduces the wastewater.

The main advantages with HIEX foam systems in general, both conventional and inside air systems, compared to other water based systems are:

- foam fills the room and prevents unrestricted air to reach the fire
- foam prevents radiation that can damage equipment
- evaporated foam decreases the oxygen content
- cooling effect
- covers and suppresses pool fires
- uses normally less water than sprinkler systems

[1)] This is the case with to days most common foam generators for inside air. The tests from 1971 described in chapter 2.4 uses water pressure driven fan.

The focus of this project is HIEX foam produced with inside air. This is a system design that has been of interest especially in the last decade and it differs from conventional HIEX foam systems in some important aspects.

- No ventilation system needed
- Positive pressure in the fire area need not to be taken into consideration
- No fan (electric or water driven) needed
- Easier and more flexible to install the system

The project was mainly divided in two parts. In order to make the study more complete and to look into earlier experience the first part was to collect and evaluate information about HIEX foam system in general and for inside air systems in particular.

As the second part of the project, a test series was conducted with a scaled HIEX foam system for inside air. The public information about HIEX foam for inside air used to protect rack storage fires in for example storehouses is very limited. Therefore it was judged that the most interesting test scenarios should be rack storage fires were the vertical fire spread is very rapid and progressive. Due to the fact that the fire spread in vertical direction and the foam builds up from beneath this scenario should be interesting. When it comes to pool fires foam in general have big advantages.

2 Literature review

The literature review includes both information about conventional HIEX foam systems in general and where available, information systems using for inside air.

The outcome of the literature review is that the information is rather limited. Especially when it comes to systems for inside air. The information is seldom official but is kept in the manufacturers possession. This is probably a result of the lack of official design criteria's for inside air systems.

The standardisation of HIEX foam systems for inside air is rather limited. There are recommendations in NFPA 11a [2], which mostly describes design for conventional HIEX foam system. NFPA 11a (1-20.9) is only briefly states that air from inside can be used if specific data for the products of combustion provides factors for increasing foam discharge. Present foam standards, ISO 7203, EN 1568 etc., do not evaluate foam concentrates for the use in HIEX inside air applications.

In order to make the background complete a historical review is presented where foam systems in general are discussed and some references that describe tests with HIEX foam systems are presented. In chapter 6 the literature review is discussed and compared with the test results from tests within this project. Especially the most interesting parameters that were influencing the results are, when possible, discussed within the references. These parameters are:

- type of system
- type of fuel
- ventilation
- activation
- volume, geometry
- application rate

2.1 Foam systems in general

Eriksson describes in [3] some tests with foam water sprinklers, i.e. small aspirating generators built as foam branch pipes, see figure 1.

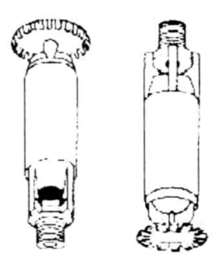

Figure 1 Example of a foam water sprinkler, which is build as small branch pipes but with a spreader at the outlet. The sprinklers were used in tests in 1958.

U.S. Naval Research Laboratories (NRL) performed tests with these foam water sprinklers in 1958, printed in NFPA QUARTERLY, JULY 1958. The fire scenario was a pool fire in a room with dimensions 20x11 m. A number of tests were performed under different condition. In all test the discharged density was 8.4 L/min/m^2 and the pool fire area was 18 m^2, 9 m^2 or 4 m^2 respectively. No information is given about room height and ventilation.

The tests were performed both with water only and with an admixture of a protein type foam concentrate. Figure 2 shows some results where tests with water only are compared to tests using foam solution. When foam was used 60 % of the water, i.e. foam solution, will stay in the remaining foam and floating on the surface. In all tests using foam the pool fire was extinguished. When only water was used 80 % of the water was evaporated and no extinction was obtained.

Tests were also performed without fire and the NRL Report has confirmed that expansion ratio have dropped from an average of 8 without fire down to 6 when the foam was produced with hot inside air.

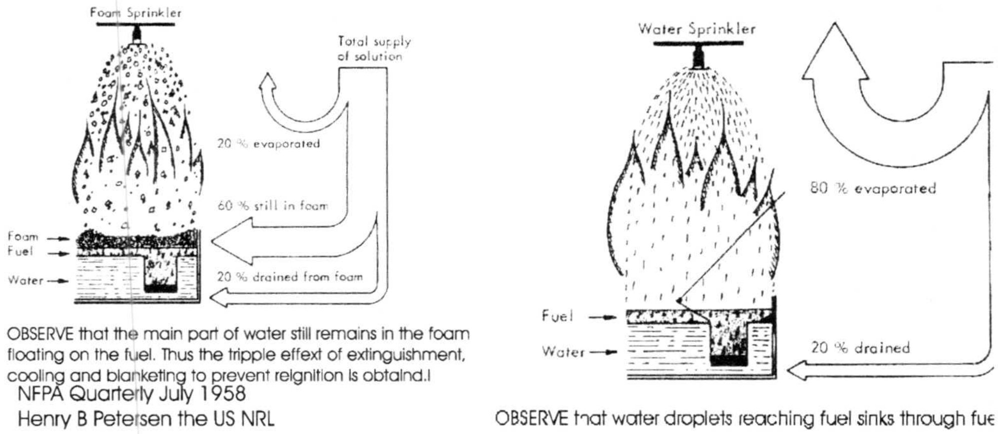

Figure 2 *Tests with foam water sprinklers, which is build as small branch pipes but with a spreader at the outlet. The tests with foam, on the left, will state that 60 % of the water will stay in the remaining foam.*

Eriksson also noted that the reported results were not discussing the size of the bubbles. According to Eriksson the smaller bubbles will destroy the bigger bubbles depending on the differences of internal pressures. Long time stable foam must be made of bubbles of the same diameter and thus have the similar internal pressure and thickness of the bubble walls. Eriksson refers to Dr Erich Manegold who gives all the relevant parameters in his book SCHAUM, published by the publishing company Strassenbau, Chemie und Technik Verlagsgesellschaft m.b.h Hedeilberg in 1953.

Eriksson also refers to a number of tests and development of foam sprinkler systems where the foam bubbles are formed in a net to produce an expansion ratio about 35. This was 1949 before the first HIEX foam systems were developed. This type of sprinkler was later developed further and was tested by SP in 1992, see chapter 2.2.

2.2 Foam systems for ship engine rooms

Since the halon fire-extinguishing systems have been phased out because of the contribution to environmental pollution and the destruction of the ozone layer, the use of an alternative have been a topical question. In later years HIEX foam systems for inside air have been used as an alternative arrangements for halon fire-extinguishing systems in machinery spaces on chips. The issue have been dealt with by the International Maritime Organization, IMO, resulting in guidelines for water-based systems, which may be installed as a replacement system for the halon system in machinery spaces and cargo pump rooms. The guidelines, MSC/Circ.668 [4], do not specific include HIEX foam systems, but the guidelines have in practice been used in order to evaluate and approve the performance of HIEX foam systems for inside air.

In SP-report 1992:37, Foam Sprinklers as a Replacement for Halon in Engine Rooms [5], different foam systems were tested as a replacement for halon in engine rooms onboard ships, i.e. machinery spaces. The project was divided in three parts:

1. Fire tests with foam sprinklers to extinguish pool fires in a machinery space
2. Fire tests with foam sprinklers to extinguish high and low pressure oil spray fires in a machinery space
3. Fire tests with high expansion foam against pool and spray fires

Some results from the report are presented in chapter 2.2.1-2.2.3.

2.2.1 Pool fires

The extinguishing tests were performed with 4, 8 and 12 m^2 pool fires in a 9x6.75 m test room with ceiling height 4.9 m. Commercial fuel oil was used as fuel. All the tests were made either with a natural fire ventilation through a door opening, 3 m high and 2 m wide, or with forced ventilation. In all tests AFFF was used as foam concentrate.

The tests demonstrated that a water sprinkler system with an additive of AFFF foam concentrate is effective against pool fires in machinery spaces with a relatively low ceiling height.

No effect of the ventilation system on the time to extinction was observed regardless of the degree of forced ventilation. However, there was natural fire ventilation through the door opening and no tests were performed in a closed room or with varying opening size. The theoretical application rate (water density) was approximately 4.1 L/min m^2 as that recommended by NFPA 11 [6].

In addition to the main test series described above some pre-tests were performed where the foam generation capacity was measured with and without smoke layer in the test room. The smoke was produced with a pool fire of 0.6 m^2. When medium expansion nozzles were used the expansion dropped from 74 with no hot smoke layer to 6 with a hot smoke layer. For low expansion nozzle the reduction in expansion was minor. The conclusion was that the use of medium expansion nozzles did not enhance performance compared to low expansion nozzles.

2.2.2 Oil spray fires

The tests with oil spray fires were performed in the same test enclosure as described in chapter 2.2.1. The tests showed that a foam sprinkler system based on high-velocity full-cone jet nozzles producing low expansion foam effectively controlled or extinguished spray fires in the simulated machinery space. The water density was 30-40 L/min m^2, corresponding to a water flow of approximately 450-600 L/min. At lower water density low-pressure spray fires were extinguished but not high-pressure spray fires.

When tested with medium expansion foam nozzles on spray fires the tests clearly showed that medium expansion foam had very little effect on the spray fire.

2.2.3 Fire tests with HIEX foam on pool and spray fires

The fire test with HIEX foam was performed with foam produced with fresh air. The same test room was used as for the fire experiments using sprinklers and no forced ventilation was used except for the air intake used for the foam generators. The door opening was covered with a net screen in order to keep the foam in the room. The foam concentrate was Sthamex SV3.

With a nominal filling rate of 1 m/min (corresponding to 100 L/min, i.e. application rate 1.64 L/min m^2, expansion ratio 610) all pool fires were extinguished.

When simulating a spray fire, the efficiency of the HIEX foam system was greatly limited. The HIEX foam was not able to extinguish or control low-pressure spray fires, while the high-pressure spray fires used in the tests, were extinguished. In the cases where the fire was extinguished the HIEX foam does not suppress the spray fire until it is extinguished. The results are opposite to those of the foam sprinkler tests. This is judged in the report to be a consequence from the larger heat release rate from low-pressure spray fires (the mass flow rate of fuel was approximately 10-15 times more in the low-pressure tests). The heat release and radiation destroyed the HIEX foam at the same rate as it was applied.

It should be noted that the flow rate between the tests with HIEX foam and water foam nozzles differ. In the case with water foam nozzles the flow rate was 450-600 L/min. A reflection from the author of this report is that it might be possible to extinguish all fires with HIEX foam if the flow rate is increased when it comes to high level fire like spray fires. No tests with higher flow rate were performed.

2.3 High expansion foam, SP-Report 1986-05

Göran Holmstedt [1] has in SP-Report 1986-05 collected information and evaluated information about HIEX foam. The report describes HIEX foam in general but some limited sections also concerns HIEX foam produced by inside air. The report is discussing four main parts:

- Foam production
- Extinguishing
- Risks for personal
- Damage to property

When SP-Report 1986-05 was published there was very limited applications on the market with HIEX foam systems for inside air. However, the research with foam produced with combustion- and pyrolysis products have been investigated since the late 1960th. Holmstedt also discusses some references, see [7 8 9]. Holmstedt shows some results from Williams [9] where the foam was produced with different temperatures of the intake air, see figure 3. It is not clear if the foam destruction is an effect of smoke or from the intake air temperature but according to Alvarez and Lipska [7] the results indicate that the foam stability is inversely related to the temperature.

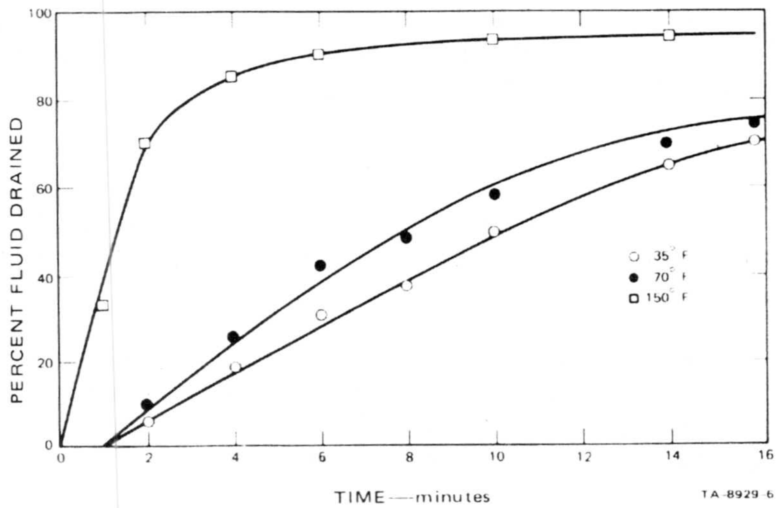

Figure 3 Effect of temperature on stability of HIEX foam.

Alvares and Lipska have also shown with a number of experiments that the foam production is affected when combustion and pyrolysis products contaminated the air used to make the foam. In figure 4 the effect of the pyrolysis products from paper and wood on production and drainage of foam are showed.

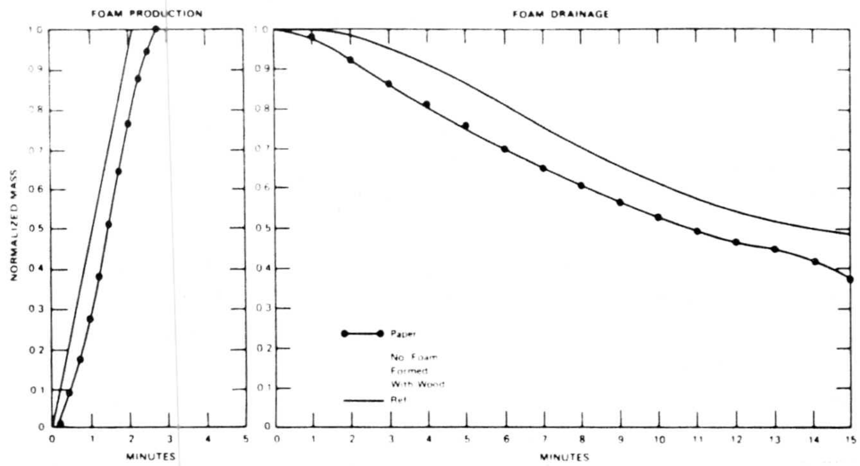

Figure 4 Effects of solid-fuel pyrolysis products on production and stability of HIEX foam.

The solid curve represents the reference run with clean air. Only data from paper are included since it was not possible to form foam at all with wood pyrolysis products. Pyrolysis products are produced when the fire is under ventilated, i.e. the access to oxygen is limited. This could be a problem if the protected enclosure is not ventilated when using HIEX foam system with inside are. Later on in this report that will be discussed in connection with the fire tests within this project, see chapter 5 and 6.

2.4 "Production of high expansion foam using air from the fire area"

In an article published in "Industribrand nr 3 1971" M.Sc. N-E Gustavsson [10] describes some test series with HIEX foam for inside air performed in Portland USA, and in Ulko-Tammio, Finland 1971. Mr Gustavsson also refers to other references and presents some conclusions based on the tests.

Tests in Portland:

The tests were performed by Gulf + Western, Rockwood Division. The number of tests made was 12. The test enclosure had an area of 17.7x11.6 m and a height of 6.4 m. The test enclosure had a natural ventilation opening in the ceiling of 1.5 m^2.

The tests were performed with relatively low located wood cribs or heptane as fuel. In some test PVC plastic was added on top of the wood crib. The fire tests with heptane were performed with 3,7 m^2 square pan filled with 95 L of heptane on a water surface. The pan was located at different heights in the different tests.

The system was activated by pneumatic rate of rise fire detection system (HAD) and the moment of activation was less than 0.5 minutes after ignition. Temperatures were measured at the ceiling, at the wood cribs and in the foam generator air inlet and foam outlet. The used foam generators operate by a water pressure driven fan. The tests made within this project, described in chapter 4 and 5, uses a different type of generator in which the foam is produced without any movable parts, see chapter 3.3.4.

Gustavssons opinion is that it is difficult to draw any final conclusions from the tests with wood cribs, since the cribs were to low, loosely stacked and their ground area was too small.

When the pan with heptane was located on the ground there was no significant decrease in foam production. The fuel surface was covered with foam before the temperature in the room had time to rise. The nominal fill rate was approximately 1 m/min.

In two tests with heptane the results were more interesting due to the fact that the results were borderline cases. In these tests the pan was located 1.2 m above the ground, which made it possible to the temperature in the room increase before the foam blanket was reaching the fire. In both tests a balanced state condition was reached when all foam production was destroyed. According to Mr Gustavsson the foam was apparently destroyed by radiated heat but another explanation could be that the resulting decrease of fill rate was a result of considerably decreased foam production. The temperature in the foam generators inlet was approximately 280°C. The difference between the two tests was that the admixture was 2.75 % and 3.5 % respectively resulting in 0.9 m/min and 1.2 m/min nominal fill rate without fire. In the test with the higher nominal fill rate the fire was finally extinguished by the HIEX foam after 8:15 (min:sec). The foam production increased slowly when the temperature decreased. The other test was manually extinguished after 10 minutes.

Test on Ulko-Tammio, Finland:

Two tests were performed in a cave, area 570 m^2 and volume aproximately 3000 m^3. The fire scenario was burning liquid on a concrete surface at the floor level. The foam generation started approximately 40 seconds after ignition.

In the first test the burning area was 30 m^2 and the burning liquid was Jet fuel (JP-1), to which 3 % petrol was added so that the burning characteristics correspond to the fuel JP-4 used in jet planes. The highest observed temperature near the cave ceiling was approximately 830°C, and the highest air temperature at the foam generator air inlet was 570°C. The fire died out without difficulty after 1 minute 21 seconds. Nominal fill rate was 1.3 m/min. The fill rate was reduced to approximately 1 m/min with the fire.

In the second test the burning area was 60 m^2 and the burning liquid was Jet fuel (JP-1), to which 6 % petrol was added. The fire died out without difficulty after 1 minute 48 seconds. Nominal fill rate was 1.1 m/min. The fill rate was reduced to approximately 0.7 m/min with the fire.

It is not clear in the reference if the fire was extinguished by the foam or if the fuel was consumed.

Conclusions made by Mr Gustavsson on the basis of the tests:

The use of HIEX foam with inside air can be approved only after careful and competent consideration, based on knowledge from full scale tests. Mr Gustavsson presents ten points with facts that he means must be taken into consideration, if use of inside air is planned. These points can be summarised in two important areas:

1. Hardware: Generators with their equipment should be fire resistant and be located close together to cover the object fast. The fire detection system must be very sensitive and operate very fast. Effective automatic smoke release openings should generally be recommended. He also suggests that the air for the generators should be taken from as a low level as possible, guided by wings.

2. Tests and experience: Tests should be performed to prove that the burning materials do not generate harmful gases and vapours to such degree that the reduction of foam generation and change of foam quality can cause danger. According to Gustafson the greatest risk seems to be the temperature of the air and he suggest that it must be considered how extensive the fire can become in the area to be protected before the foam has extinguished it. The temperature might in some cases be calculated or be available from other fire tests. More large scale tests should be carried out. Tests in small scale to investigate the chemical-physical effects of gases from the fire on the foam should be checked under conditions, which correspond to large scale.

A reflection from the author of this report is that no tests were performed in order to investigate the influence of ventilation. Fire tests performed in this report, see chapter 4 and 5, showed that the ventilation and/or the size of the test enclosure influence the foam production. If the test enclosure is small with small ventilation openings the foam production might decrease because of high temperature, steam and produced pyrolysis products. Alvarez [7] showed that the foam production was decreased considerable when pyrolysis products were used for foam production.

Another reflection is that the foam concentrates that were used in the 1960-70th were synthetic foams that was developed for conventional HIEX foam systems. During the 1980-90th the foam concentrates used in inside air systems has been developed and are designed to be more resistant for inside air, i.e. combustion products etc.

3 Test set-up for the experiments

The experimental part of the project was aimed towards the use of HIEX foam for inside air systems used to protect high rack storage fires. This is a scenario which differs considerable from pool fires due to the vertical fire spread is very rapid and progressive. Earlier tests and experience on foam systems in general have indicated a big advantage compared to other systems when it comes to pool fires at low levels due to the fact that the foam blanket cover the fuel surface. However, the aim with the tests in this project was to arrange test scenarios were a HIEX foam system for inside air was challenged by vertically spreading fire.

In order to limit the costs and being able to perform tests inside the SP fire hall under controlled conditions the tests were performed in a reduced model scale, 1:3 scale.

Parameters of interest that have been varied between tests are:

- Filling rate
- Activation criteria
- Ventilation (only natural ventilation)
- Room height
- Type of goods

3.1 Pre-test

In order to design a suitable test enclosure and to predict the expected heat release from a fire in rack storage, some free burning pre-tests were performed. The idea was to work in 1:3 scale and therefore a scaled rack storage was constructed, see chapter 3.3. In addition to the rack storage, a pile of cartons was placed 0.73 m from the rack as a target in order to record the spread of fire. The tests were performed in SP:s fire hall and the heat release rate (HRR) was measured with SP:s 10 MW Industry Calorimeter. Two different fuels in the rack storage were used, plastic cups and wood wool (see chapter 3.3.2). The maximum HRR was approximately 4.5 MW for the plastic cup scenario and approximately 3 MW for the wood wool scenario, see figure 5.

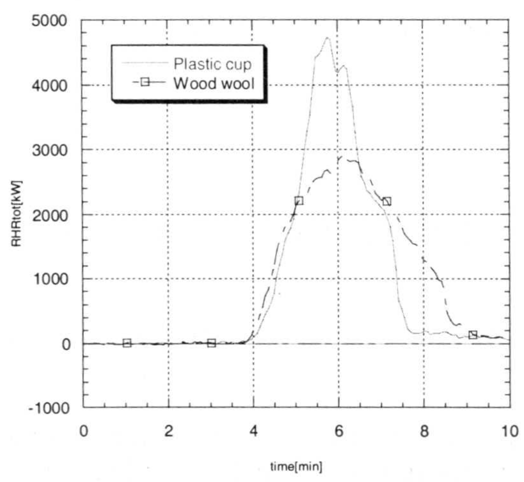

Figure 5 Results from the pre-tests with free burning rack storage.

In both pre tests the rack storage was ignited two minutes after start of measuring. The peak HRR appeared approximately 4 minutes after ignition. Approximately 0.5 minutes before the peak HRR occurred the targets were ignited by the radiation from the rack storage fire. The test with plastic cups was manually extinguished at 5:20 (min:sec) after ignition and wood wool test after 6:30 (min:sec).

Based on the results from the pre tests it was decided to use the same configuration for the rack storages in the main test series, see chapter 3.3.2.

3.2 Scale modelling

The fire tests were performed in a rather small enclosure compared to a conventional full size storage building or an industrial building. This was decided in order to make it possible to perform a number of tests in the project to a reasonable cost. The intention with the test enclosure used was that the test should be performed in 1:3 scale. The design basis was a storage enclosure with an area of 30x30 m and a height of 9 m which correspond to 10x10 m and 3 m in 1:3 scale. To reduce the amount of goods it was decided to use three rack storages with goods as fuel in the test enclosure, see chapter 3.3.

The problem with testing in a model scale is the lack of complete dynamic similarity, i.e. flow similarity between full scale and model scale. When the results in the model scale are used to predict results in full scale, i.e. real scale, a number of dimensionless groups should be preserved. The ratios between forces involved, in addition to the geometrical similarity, must be equal. This is not possible to manage without increasing the pressure in the model scale. The model used in this project, to describe expected values in full scale, is based on that Froude Number (*Fr*) is constant between the two scales, see Drysdale [11] and Ingason [12]. This is possible if viscous forces are relatively unimportant, i.e. Reynold number (*Re*) is high. The *Fr* is given by:

$$Fr = \frac{u^2}{\mathrm{lg}}$$

where u is the velocity, l is a characteristic length and g is the specific gravity.

Based on that *Fr* is constant between two scales the following relationship is obtained between parameters in model scale (x_M) and full scale (x_F):

$$x_F = x_M \left(\frac{SF_F}{SF_M} \right)^e$$

where SF_M is the model scale factor, equal to 1, and SF_F is the full scale factor, equal to 3.

The exponent, e, is determined by the parameter in question in order to conserve the geometric similarity.

Table 1 presents an example with simulated figures for the model scale and calculated figures for the full scale scenarios based on the *Fr* modelling. During the planning of the performed test series, the scale modelling was used in order to make sure that parameters chosen were reasonable. No confirming test in full scale have been performed, but during the planning of the performed test series the scale modelling was considered.

Table 1 *Example of relationship between model scale and full scale based on Fr modelling. The input figures are representative for the fire scenarios presented later in this report. The shaded cells represents calculated values.*

Parameter	**Model scale**	*e*	$\left(\frac{SF_F}{SF_M}\right)^e$	**Full scale**
Premix flow rate/gen. (L/min)	20.5	not relevant	not relevant	90
Geometric Scale Factor, SF (-)	1.00	not relevant	not relevant	3.00
Expansion ratio (-)	440.00	0*	1.00	440.00
Width (m)	10.00	1	3.00	30.00
Lenght (m)	10.00	1	3.00	30.00
Height (m)	3.00	1	3.00	9.00
Volyme (m^3)	300.00	3	27.00	8100.00
HRR (kW)	1000.00	2.5	15.59	15588.46
Filling rate (m/min)	1.62	0.5	1.73	2.81
Foam flow rate (m^3/min)	162.00	2.5	15.59	2525.33
Submergence time (min)	1.85	0.5	1.73	3.21
Premix flow rate (L/min)	368.18	2.5	15.59	5739.39
Extinguishing time (min)	3.00	0.5	1.73	5.20
Temp (°C)	300.00	0	1.00	300.00
Ventilation (m^3/min)	170.00	2.5	15.59	2650.04
Number of generators (-)	18	not relevant	1.00	64

* In theory the expansion ratio should be scaled, due to the fact that size of bubbles, internal pressure etc. should be different in different scales. This has not been considered.

As seen in the table, different parameters change from scale to scale in different ways to preserve the geometric similarity and *Fr*. As mentioned before the results are not fully comparable because of the lack of complete dynamic similarity, especially since the pressure in the test enclosure was not controlled. Other questions are how the radiation from the fire influences the foam destruction in different scales and how the foam quality (expansion ratio and drainage time) influences the scale. This has not been investigated. The expected values, for the full scale scenario, presented in the table are only an intimation and have to be confirmed by full scale tests if any certain conclusions are to be done.

However, the results from the model scale should give a good picture of some aspects and it is important to be aware of how the scale influences the results. For instance a specified filling rate, 1.62 m/min, in the model scale corresponds to larger, 2.81 m/min, in the full scale. A fully developed fire in one rack storage in the model scale was measured to 4.5 MW (see chapter 3.1), which corresponds to 70 MW in full scale! In the test series performed in the test enclosure described later on, the maximum HRR was calculated [1)] to be approximately 0.8-3 MW depending on the start condition and the ability for the system to control the fire.

[1)] The HRR was calculated from the oxygen concentration and mass flow rate in the ceiling openings.

3.3 Experimental set-up

The experimental arrangement is shown in figures 6-8. The rack storage consists of a steel frame where 32 cartons were placed as shown in the figures simulating 32 pallet loads. The cartons were placed directly on the steel frame and no wood pallets were used.

3.3.1 Test room

The design basis for the test room was a storage enclosure with an area of 30x30 m and a height of 9 m corresponding to a test room with an area 10x10 m and a height of 3 m or 4.2 m, see figures 6 and 7. The wall of the test room was constructed using wood beams and non-combustible, nominally 8-12.7 mm thick, wallboards. The ceiling was constructed of the same non-combustible was boards mounted in steel frame system. The ceiling in the centre of the test enclosure was insulated with 50 mm rockwool and covered with a steel plate as protection against heat exposure.

At each sidewall, a 1.11 m wide opening was placed in order to enable natural ventilation. The height and vertical position of the openings were varied between the tests, but in the main part of the tests the area of each opening was 0.5 m^2 and the upper end of the opening was positioned 2 m above the ground. In some tests the opening was 1 m^2 with the lower end 0.9 m above floor level. In order to prevent the foam flowing out through the door openings, the openings were equipped with a steel net of nominal 5 mm metal mesh. In the ceiling one ventilation opening at each corner were placed as shown in figure 6. The size of the openings was varied between the tests. The door opening was closed during all tests.

Figures 6 and 7 also shows the HIEX foam inside air system and the generators are described in chapter 3.3.4.

Three rack storages, as described in chapter 3.3.2, were placed symmetrical in the test room as shown in figures 6 and 7. In all tests the centre rack storage was filled with goods, i.e. plastic cups or wood wool. In all tests, except for tests T02 and T03, the two surrounding rack storages were filled with empty cartons at the lowest tier and at the outermost position in the three lowest tiers. In most cases, when the fire was spread to the surrounding rack storages, only the filled cartons were involved in the fire. In tests T02 and T03 the two surrounding rack storages were filled with empty cartons.

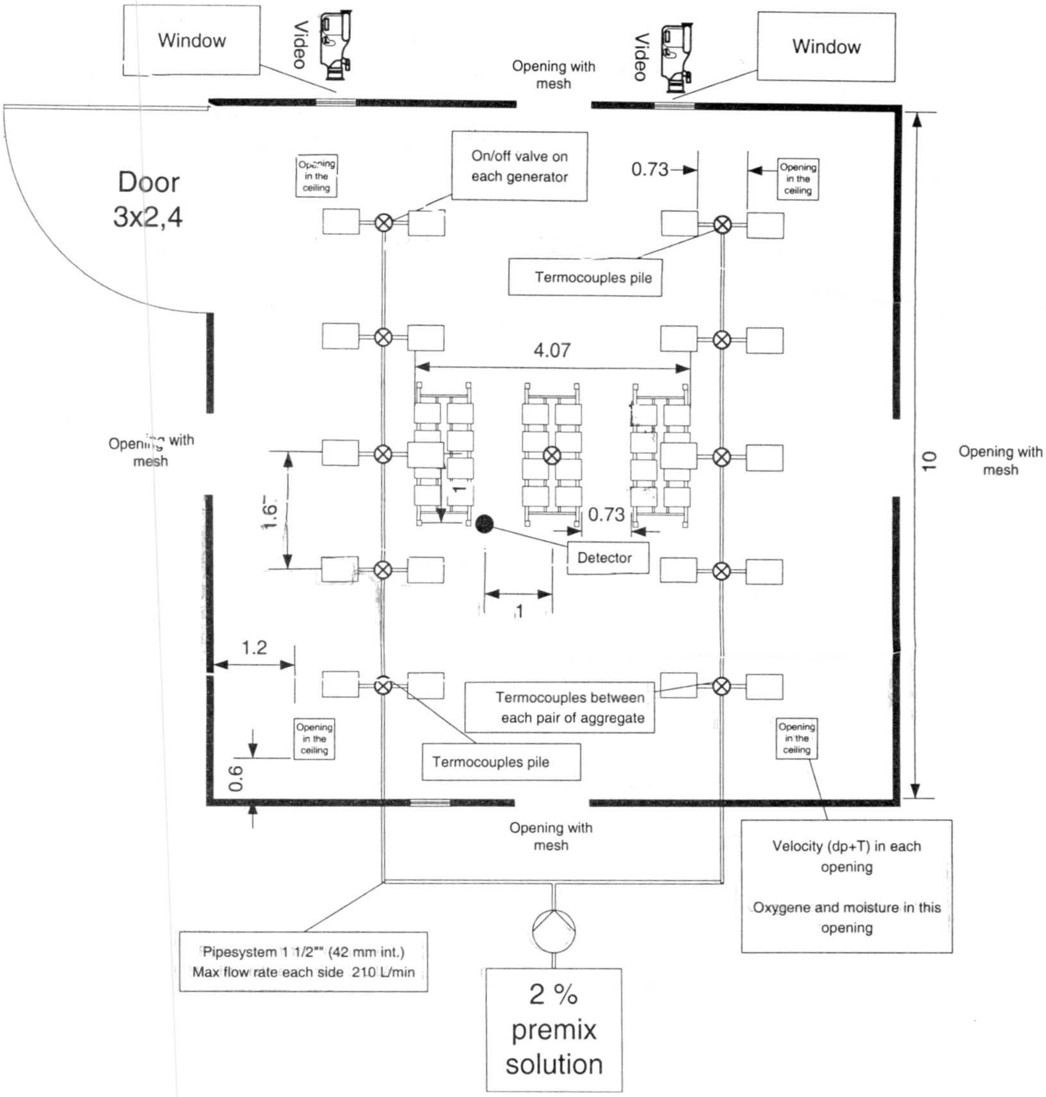

Figure 6 Plan view of the test enclosure. Dimensions in metres.

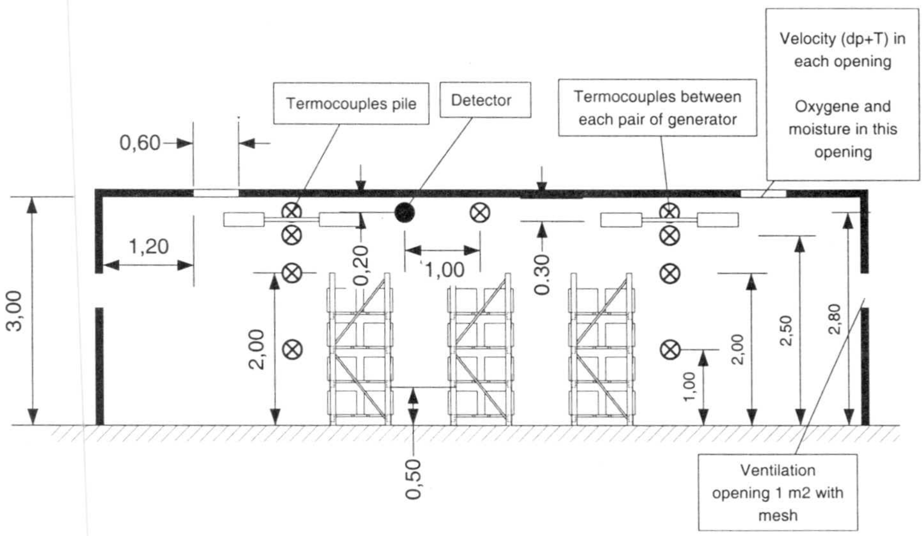

Figure 7 Side view of the test enclosure. Dimensions in millimetres.

3.3.2 Rack storage

The rack storages were constructed from steel frames as shown in figure 8. In all tests four tiers, with eight cartons on each tier, were used. At the lowest tier in the middle rack storage, four ignition sources were symmetrically mounted at the bottom of each carton, see figure 8. The ignition source consisted of a 12 mm insulating fibre board measuring 17x17 mm, soaked with 2.8 ml heptane and wrapped in a polyethylene bag.

The cartons were made of 4 mm thick double wall corrugated cardboard. In the bottom of the carton one extra cardboard sheet was placed.

Two different materials were used as fuel in the cartons, plastic cups and wood wool.

The plastic cups were made from polystyren with dimension 90 mm height and 85 mm in top diameter. The weight of each plastic cup was 28 grams. Each carton contained 36 plastic cups divided in three layers with one cardboard frame to support the plastic cups and one cardbord sheet between each layer.

For the tests with wood wool, 1 kg of wool was placed in each carton.

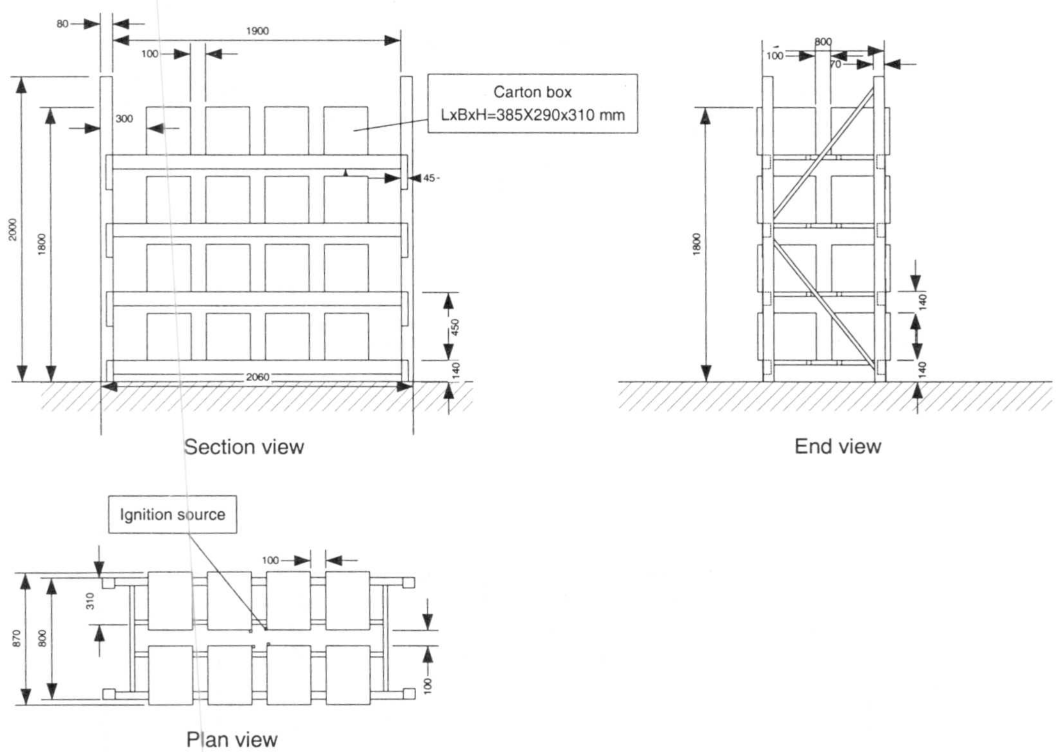

Figure 8 Rack storage in three different views. 32 cartons were used on each rack storage to simulate 32 pallet loads. Dimensions in millimetres.

3.3.3 Measuring and recording

During the fire tests a number of measurements and recordings were conducted. In figures 6 and 7 all the measuring devices are shown. The measurements were made using a data logging system which recorded data every second.

The temperature was measured between each pair of generators 0.2 m beneath the ceiling using 0.25 mm thermocouples (TC). These measuring points are designated Generator No.1, Generator No. 2 etc. referring to the location of each pair of generator starting with No. 1 in the low left in figure 6. In addition to these temperature measurements, the temperature was also measured at different heights at Generator No. 1 and 6, see figures 6 and 7. One TC was also located in the centre of the test room, i.e. 0.2 m beneath the ceiling above the centre rack storage, designated Temp. ceiling.

One specially designed TC was used to define the activation criteria during the fire tests. The simulated detector was made of a 1 mm TC that was sheathed with a brass rod with diameter 4 mm and length 15 mm. The 1 mm TC was fitted in the brass rod half way in the length direction. If not stated otherwise the detector was located as shown in figure 7, i.e. diagonally 1.41 m from the centre and 7.5 cm under the ceiling (not in tests T02 and T03).

Note: The activation criteria in most tests were when the temperature reading of the simulated detector reached 68° C or 141°C. In practice these temperatures were reached approximately 10-15 seconds and 25-30 seconds respectively, after the flames reached the ceiling.

In the ventilation openings in the ceiling the velocity was measured with a bi-directional probe, which measures the temperature and the difference between the static and the total pressure, Δp. In one of the ventilation openings in the ceiling, instruments for measuring oxygen concentration and water content were mounted. The oxygen content and the velocity were used to calculate the heat release rate (HRR) from the fire [13]. The calculations were made in order to estimate the HRR during the tests. The peak HRR was estimated to 0.8-3 MW depending on the start condition and the ability for the system to control the fire.

In addition to the measurements described above all tests were recorded with two video cameras in order to make it possible to study the tests afterwards.

3.3.4 HIEX foam inside air system

The HIEX foam inside air system used in the tests was delivered by Svenska SKUM AB. It consisted of 20 generators located as shown in figure 6 and 7. The foam generators are rather small and only used for experimental purpose, which make them suitable for using when testing in 1:3 scale. A schematic sketch of the foam generator is shown in figure 9.

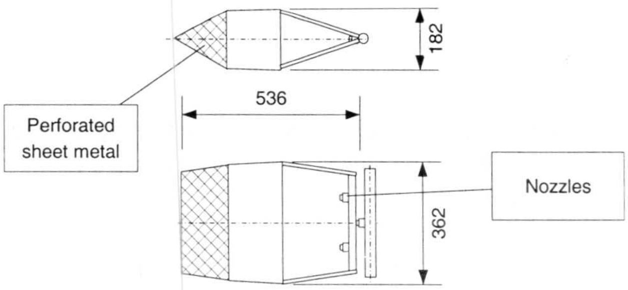

Figure 9 *Foam generator used in the HIEX foam inside air system during the reported tests. Dimensions in millimetres.*

The foam is produced without any electrical power supply to the generator and no fan is used. The generators do not include any movable parts. At an inlet pressure of 6 bar the volume flow rate is 20.5 L/min corresponding to nominal 9 m^3/min, i.e. a foam expansion ratio of 440.

The foam generators were installed 0.3 m beneath the ceiling in groups of two generators as shown in figure 6 and 7. The generators were connected to a piping system supplying 2% premix solution from a 4 m^3 storage tank.

The used foam concentrate is a part of the system and therefore only one type of foam concentrate has been used. The foam concentrate is developed to be a component in the HIEX inside air system. It should be noted that different kind of foam concentrates might give other results and has to be considered when designing a system. However, from general knowledge it is known that ordinary HIEX foam concentrates are not useful in HIEX inside air systems.

Each foam generator was equipped with a stop valve to make it possible to disconnect a number of foam generators in order to adjust total volume flow rate. In all tests except for test T16 the centre generators directed towards the centre rack storage were disconnected. In test T16 the centre generators was activated in order to show the influence of direct application.

4 Experiments

4.1 Test procedure

All test were performed in a similar way but with different start conditions. The data logging system was started 2 minutes before ignition which means that the time information given in the results are related to 00:00 (min:s) at start of logging system.

The HIEX foam inside air system was manually activated. After activation approximately 8-16 seconds followed when the system was filled with premix before foam was produced. Specific time to activation for each test is given in table 3 summarising the test results.

All tests were recorded with video in addition to visual observations during the tests. The video was examined and analysed after the tests and the observations during the tests were taken in to account when the results were evaluated. Especially the foam height in the room was estimated from the video recordings. Diagrams with the foam height and temperatures from a selective number of tests are presented in chapter 5.2.

4.2 Test scenarios

In total 23 tests were performed. Table 2 summarises the fire scenarios used in the test series.

The columns in the table are as follows:

Test No.:	Refers to tests in chronological order.
Activation criteria:	Temperature reading of the simulated detector when the system is activated (See note regarding T19, T20, T21 and T23)
Goods:	Type of goods.
Ventilation in ceiling:	Total size of the ventilation openings in the ceiling.
Ventilation in wall:	Total size of the ventilation openings in the walls.
Number of generators:	Number of generators used in the test.
Total flow rate:	Total nominal premix flow rate.
Application rate:	Calculated mean application rate.
Nominal filling rate:	Nominal filling rate without fire. Calculated with expansion ratio of 440.
Ceiling height:	Ceiling height of the enclosure.

Table 2 *Test scenarios used in the test series.*

Test No.	Activation criteria	Goods	Ventilation in ceiling (m^2)	Ventilation in wall (m^2)	Number of generators	Total flow rate (L/min)	Application rate (L/min/m^2)	Nominal filling rate (m/min)	Ceiling height (m)
T01	Filling test without fire	Empty test room	1.44	2 [1)]	18	369	3.69	1.62	3
T02	68 °C [2)]	Plastic cup [2)]	1.44	4 [1)]	18	369	3.69	1.62	3
T03	68 °C [2)]	Plastic cup [2)]	0.72	2 [1)]	18	369	3.69	1.62	3
T04	68 °C	Plastic cup	0.36 [3)]	0	18	369	3.69	1.62	3
T05	68 °C	Plastic cup	1.44	2	18	369	3.69	1.62	3
T06	68 °C	Plastic cup	1.44	4 [1)]	18	369	3.69	1.62	3
T07	141 °C	Plastic cup	1.44	4 [1)]	18	369	3.69	1.62	3
T08	141 °C	Plastic cup	1.44	2	18	369	3.69	1.62	3
T09	141 °C	Plastic cup	1.44	2	18	369	3.69	1.62	3
T10	68 °C	Plastic cup	1.44	2	8	164	1.64	0.72	3
T11	68 °C	Wood wool	1.44	2	8	164	1.64	0.72	3
T12	68 °C	Plastic cup	1.44	2	12	246	2.64	1.08	3
T13	68 °C	Wood wool	1.44	2	12	246	2.64	1.08	3
T14	68 °C	Plastic cup	0.36		12	246	2.64	1.08	3
T15	Filling test without fire	Empty rack storage	1.44	2	18	369	3.69	1.62	3
T16	68 °C	Plastic cup	1.44	2	12, direct application	246	2.64	1.08	3
T17	No activation	Plastic cup	1.44	2	0	0	0	0	3
T18	68 °C	Plastic cup	1.44	2	12	246	2.64	1.08	4.2
T19	28 s after flames at tier 4 [4)]	Plastic cup	1.44	2	12	246	2.64	1.08	4.2
T20	Flames at tier 4 [5)]	Plastic cup	1.44	2	12	246	2.64	1.08	4.2
T21	Flames 1.5 m above rack storage [6)]	Plastic cup	1.44	2	18	369	3.69	1.62	4.2
T22	68 °C	Wood wool	1.44	2	12	246	2.64	1.08	4.2
T23	Flames at tier 4 [5)]	Plastic cup	1.44	2	8	164	1.64	0.72	4.2

[1)] The ventilation opening was placed with the lower end 0.5 m above floor level.
[2)] The detector was placed 15 cm beneath the ceiling. Empty cartons in the surrounding rack storages.
[3)] Only two ventilation openings were used.
[4)] The activation criteria correspond to the time when the temperature reached 68°C in the 3 m test room.
[5)] Faster activation than other tests.
[6)] Activated when the flames visually were the same as in tests in the 3 m test room and 68°C activation.

5 Results and discussion

The results from the test series are summarised in table 3, with some judgements of the outcome from each test. Graphs showing the foam height and temperature at one location, Generator No. 1, from all tests are summarised in figure 10. The table and the graphs are preferably used to get an overview of the test results together with table 2 where the start conditions for each test are presented.

Further on, the results are presented in diagrams where tests with almost similar start conditions, meaning that only one parameter differ between the tests, are compared. This gives relative data that has been used to draw conclusions on the influence of each parameter.

5.1 Summary of test results

Observe that the times given in the results is the time from when the measurements commenced, i.e. 2 minutes before ignition.

The columns in the table are as follows:

Test No.:	Refers to tests in chronological order.
Start of foam system:	Time for start of foam system, i.e. when the activation criteria is fulfilled.
Foam filling rate:	Subjective judgement of the foam filling rate during the test. The foam height versus time is presented in diagrams.
Fire spread to surrounding rack storage:	The time to ignition of the surrounding rack storage(s).
Minimum oxygen concentration:	The measured minimum oxygen concentration in the outlet of one ventilation opening in the ceiling.
Time to extincion:	The time to extinction was judged from thermocouple readings during the tests and from visual observations, both from notes during the tests and from video recordings.
Comments:	Comments if any.

Table 3 Summery of test results

Test No.	Start of foam system (min:s)	Foam filling rate	Fire spread to surrounding rack storage (min:s)	Minimum oxygen concentration (Vol %)	Time to extinction (min:s)	Comments
T01	02:00	1.8 m/min	Not applicable	Not applicable	Not applicable	
T02	04:13	Poor	05:20	15.4	Not achieved	Empty cartons in surrounding rack storages [1)]
T03	04:13	Poor	05:30	15.4	Not achieved	Empty cartons in surrounding rack storages [1)]
T04	04:09	Good	No	16.3	06:30	
T05	04:16	Good	No	17.9	06:45	
T06	04:20	Good	No	17.7	06:20	
T07	04:37	Quite poor	No	15.3	Not achieved	
T08	04:56	Good	06:50, only very limited	16.6	09:00	
T09	04:38	Quite poor	05:36	15.7	09:00	
T10	04:23	Very poor	05:37	11.2	Not achieved	
T11	04:12	Very poor	05:48	14.8	Not achieved	
T12	04:20	Poor	05:43	14.8	Not achieved	
T13	04:22	Poor	06:21	16.7	Not achieved	
T14	04:23	Quite poor and decreasing	06:00	12.6	Not achieved	No foam production after 08:00
T15	02:00	2 m/min	Not applicable	Not applicable	Not applicable	
T16	04:17	Good but decreasing	No	17.4	13:30	Direct application
T17	No foam application	No foam application	05:28	8.6	Not applicable	
T18	04:45	Quite poor	06:04	15.2	Not achieved	
T19	04:43	Quite good	05:55	16.0	Not achieved	
T20	04:06	Good but decreasing	No	18.2	07:15	
T21	04:30	Good	No	18.6	06:30	
T22	04:22	Good	No	17.2	09:00	
T23	04:10	Good in the beginning but decreasing	06:08	15.0	Not achieved	

[1)] The poor foam production was probably caused by the fast fire development in the empty cartons in the surrounding rack storages. The surrounding racks were ignited despite the 68°C activation and high application rate. In all other tests the surrounding rack storages were filled with plastic cups or wood wool as described in chapters 3.3.1 and 3.3.2.

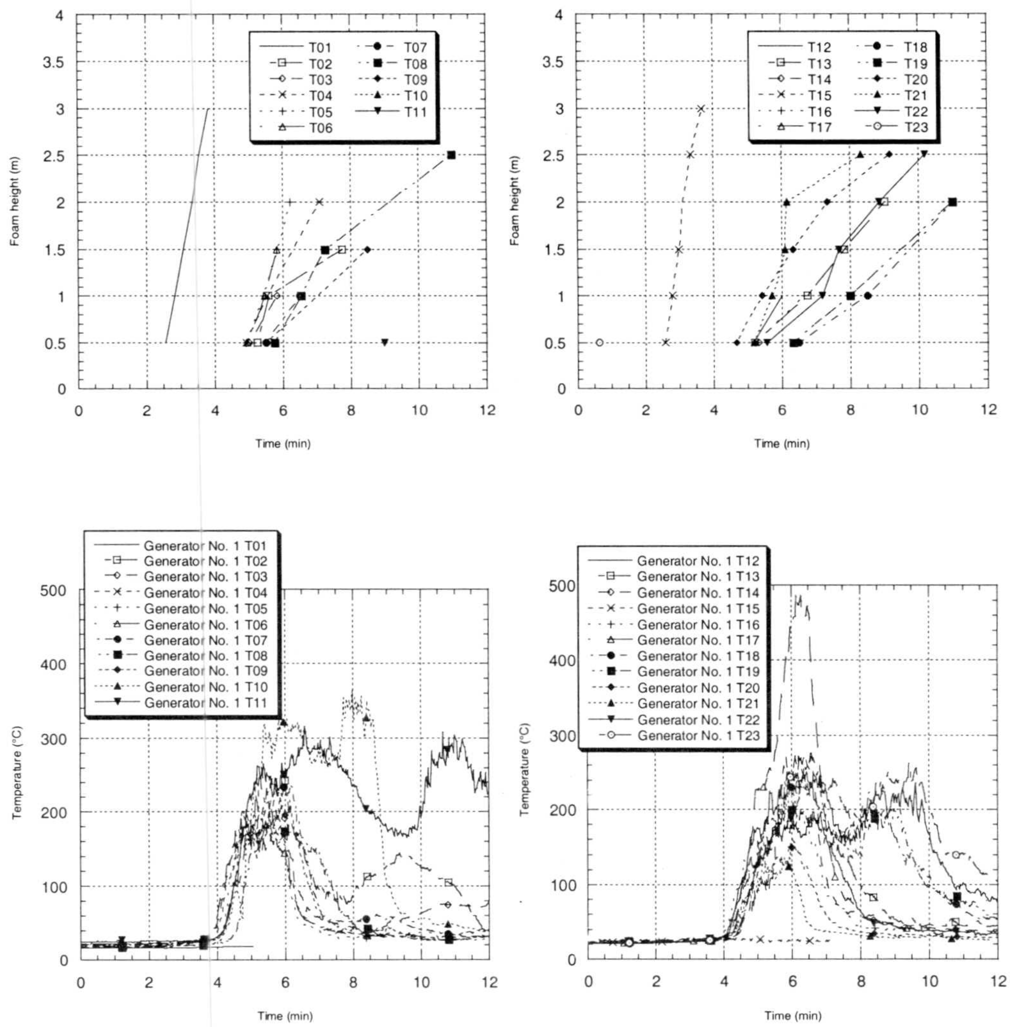

Figure 10 Foam height and temperature at generator 1 versus time for all tests. On the left T01-T11 and on the right T12-T23.

5.2 Results from tests with comparative start conditions

In order to get relative results from the fire tests some results from tests with similar start conditions, except for one parameter, have been compared. The results are presented in graph were the foam height and the corresponding temperature at generator No. 1 are given. The comparative tests are given in the same graph and the conclusions are given in connection to each graph.

Application rate:

Three different application rates were used in the test series using 8, 12 or 18 foam generators corresponding to nominal application rate 1.64 L/min m^2, 2.46 L/min m^2 and 3.69 L/min m^2.

With the lowest application rate, test T10, the foam build up was very limited and was less than 0.5 m during the entire test. As been seen in figure 10 the temperature in test T10 is above 300 °C and increasing.

In test T12 the fire was at first controlled but was spread to the outer rack storages at 05:45 and the fire was increased after 8 minutes.

In test T05 the application rate was enough to put out the fire in the centre rack storage before the fire spread to the surrounding rack storages. The temperature was rather moderate and foam was able to build up and cover the full height of the rack storages.

As can be expected the higher application rate, the better foam production and foam build up and lower temperatures was obtained. With the start condition used in these tests the highest application rate, i.e. 3.69 L/min m^2, was needed to control the fire before it was spread to the surrounding rack storages.

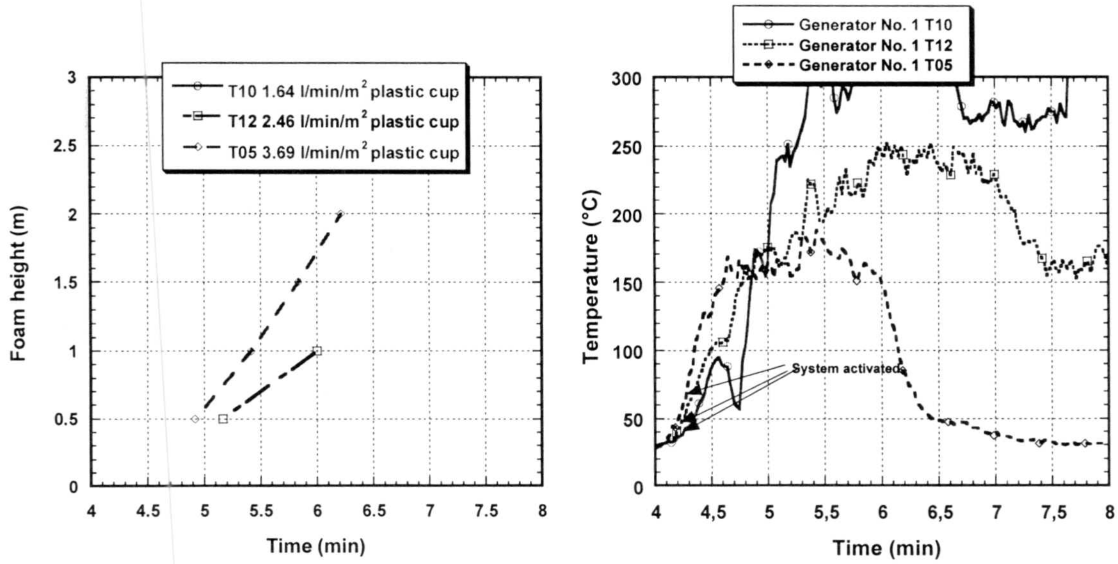

Figure 10 The average foam height in the test room and temperature at generator No.1 in tests T10, T12 and T05 with different application rates.

Activation criteria:

Two tests with different activation criteria are shown in figure 11. In both tests 18 foam generators were used.

In test T07 the system was activated when the detector reached 141°C. This resulted in that the fire was spread to the surrounding rack storages before the fire was controlled. However, the high application rate compensated the late activation time and the foam was covering the entire floor area and reached approximately 1 m up on the centre rack storage. This was enough to reduce the fire and control was achieved. However, the fire was not completely extinguished by the foam system.

With activation at 68°C, test T06, the system was able to produce good quality foam which built up rather quickly and extinguished the fire in the centre rack storage before the fire spread to the surrounding rack storages.

As can be expected the earlier activation time, the better foam production and foam build up and lower temperatures were obtained. With 18 foam generators the fire was controlled in both cases, i.e. activation at either 141°C and 68°C respectively.

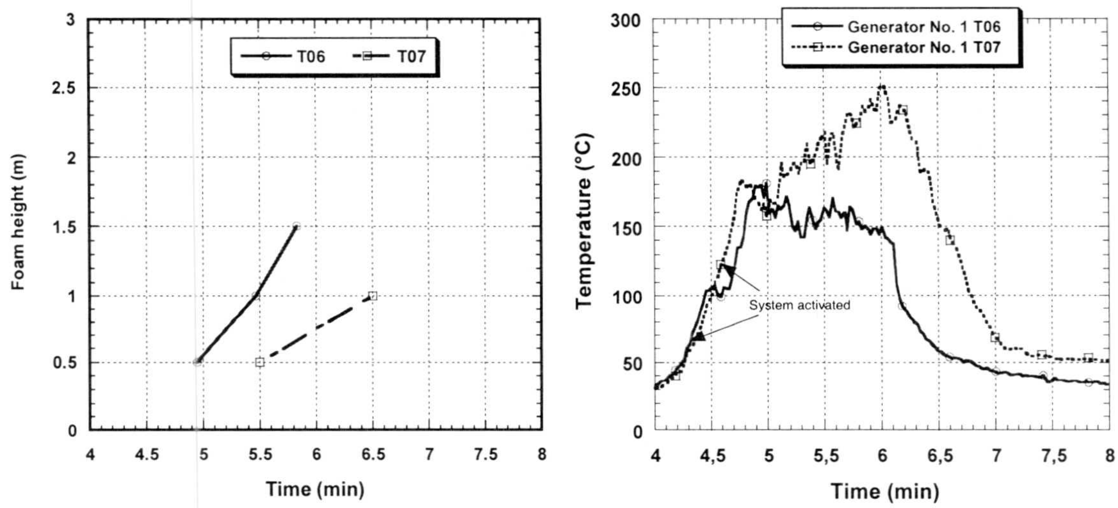

Figure 11 *The average foam height in the test room and temperature at generator No.1 in tests T06, and T07 with different activation criteria.*

Ventilation:

The test results from tests with different ventilation are presented in three different pairs of diagrams in order to point out different phenomena. The oxygen content is given in one diagram to illustrate and explain the course of events during the tests.

Three tests with different ventilation openings are shown in figure 12. In all three tests 18 foam generators were used. The difference between test T05 and T06 are only the size and position of the openings in the walls. In test T04 the openings were smaller in the ceiling compared to the openings used in the other two tests and there was no openings in the walls. As shown in figure 12 the foam build up was a little bit less when the smaller ventilation openings were used.

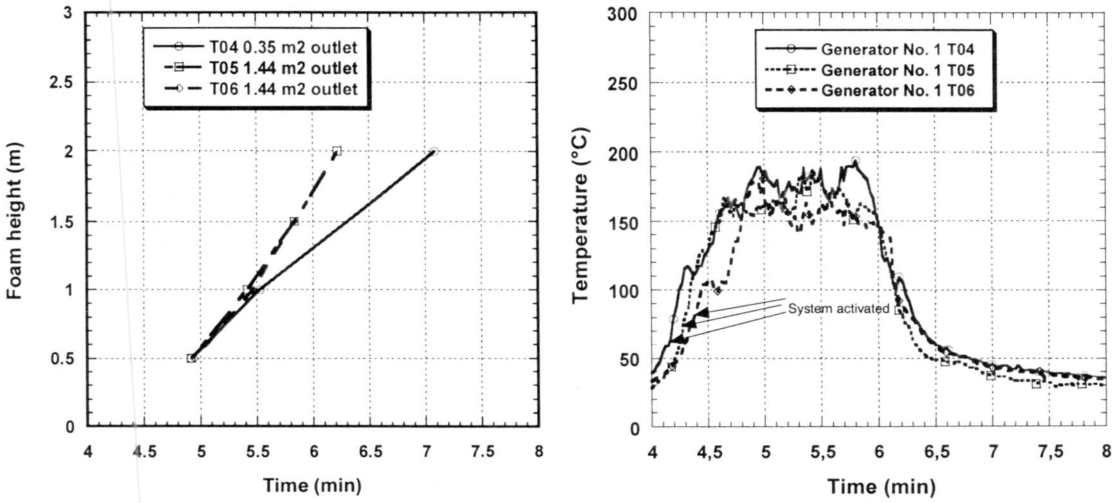

Figure 12 *The average foam height in the test room and temperature at generator No.1 in test T04, T05 and T06 with different ventilation openings.*

In tests T12 and T14, see figures 13 and 14, 12 foam generators were used. In this case the results are different between the test with small ventilation openings and the test with larger ventilation openings. When using the small ventilation openings, T14, the temperature in the test room was initially increasing slower and began decreasing at approximately 06:40.The peak temperature was rather high. The surrounding rack storages were ignited at 06:00. The foam production was limited and at 08:00 no foam production was noted despite the low temperature.

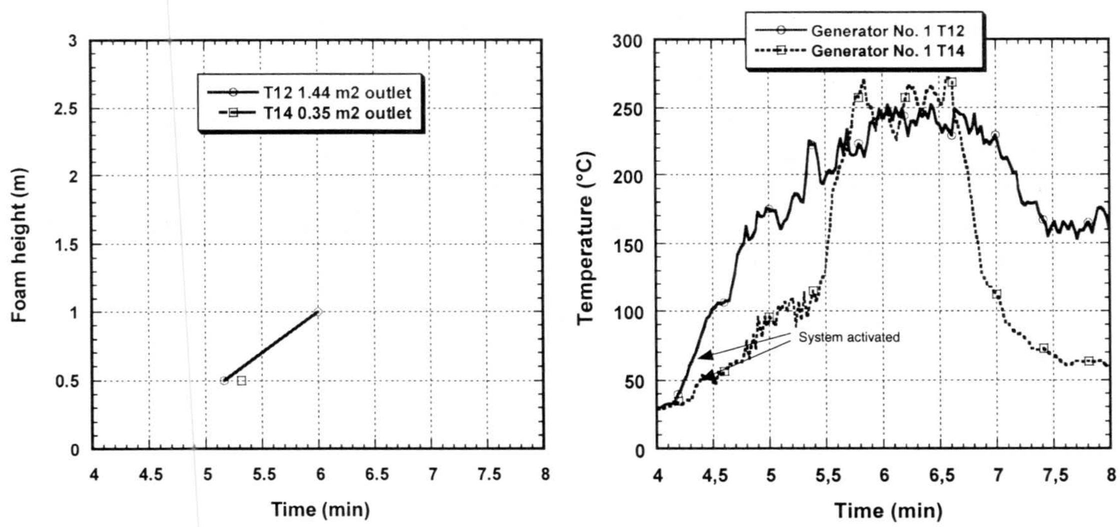

Figure 13 *The average foam height in the test room and temperature at generator No.1 in tests T12 and T14 with different ventilation openings.*

In figure 14 the same tests are illustrated but with an extended time scale and with the measured oxygen concentration. As one can see oxygen concentration is very low when the temperature is reduced. The fire is probably reduced because of lack of oxygen. At 13:00 the fire is again increasing probably when oxygen is reaching the fire. (Note: The rapid increase of oxygen concentration in test T14 is caused by fresh air was sucked in to the opening where the measuring devise was located. This was confirmed by that the velocity in the opening was suddenly changing direction.)

The fire development in test T14 might be an indication of that the fire was under ventilated and producing not only combustion products but also pyrolysis products that influenced the foam production negatively. The smoke layer in the test room was reaching the fire source, which indicates that the fire might be under ventilated.

Another explanation for the very poor foam production could be that steam and re-circulated water spray reached the air inlet of the generators. The result should be that the volume of produced foam is very limited.

In the case with larger ventilation, i.e. test No. T12, the foam build up was better and no reignition occurred.

The conclusion is that the *HIEX foam*-system using inside air works in different ways depending on the ventilation. If the system shall work in an enclosure where the ventilation are such as the fire becomes under ventilated this have to be considered during the design of the system. If the protected area have limited ventilation compared to the volume and that one can expect that the fire will become under ventilated the system should be designed as a water spray system. This means that the application rate should be increased to ensure control without foam production.

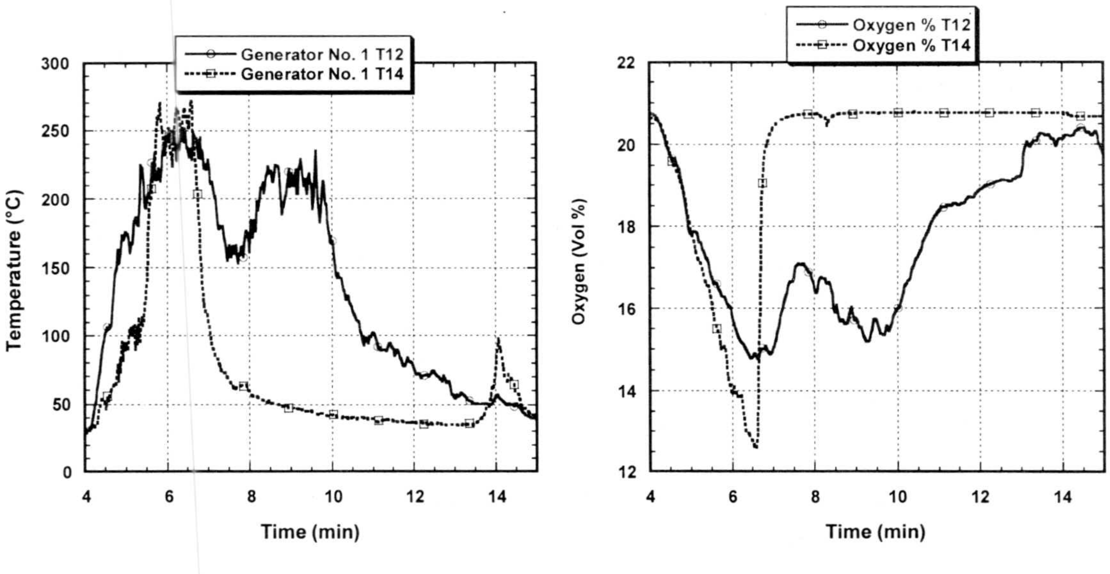

Figure 14 The temperature at generator No.1 and oxygen concentration in tests T12 and T14 with different ventilation openings. The time scale is extended in order to show the reignition in test T14. (Note: The rapid increase of oxygen concentration in test T14 is caused by fresh air was sucked in to the opening where the measuring devise was located. This was confirmed by that the velocity in the opening was suddenly changing direction.)

Different goods:

Only two different types of goods were used in the test series. Figure 15 shows two test results from tests with plastic cups and wood wool respectively. In both tests the system was activated at 141°C on the detector. With wood wool the peak temperature is lower and the foam build up is slightly better than with the plastic cups. With plastic cups the temperature is decreasing faster. In general it was harder to obtain complete extinction when using wood wool but the fire was easier to control due to the better foam build up.

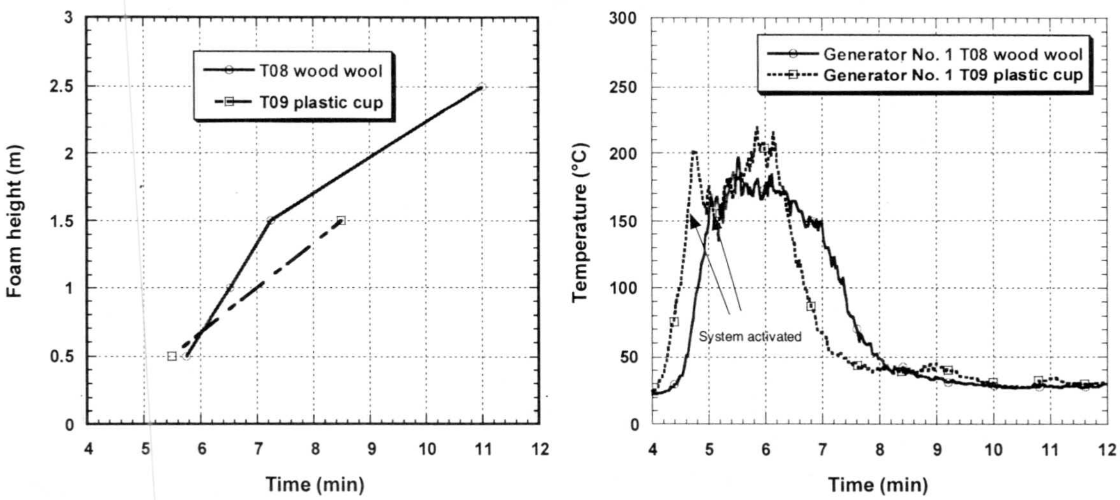

Figure 15 *The average foam height in the test room and temperature at generator No.1 in tests T08 and T06 with different goods.*

Ceiling height:

In total 6 tests were conducted with 4.2 m ceiling height. In the test series, five different activation criterias were used. In addition to the 68°C activation temperature on the detector, the system was activated when the flames reach a specific height. This was done in order to simulate the same visual activation as in the tests with 3 m ceiling height.

The results were that the foam build up rate and the temperatures were similar when the 68°C activation criteria was used in both tests, see figure 16. This was a little bit surprising because of the fact that the fire in the 4.2 m test room was considerable larger when the system was activated compared to the test with the 3 m ceiling height. The explanation for the similar result is probably the larger volume and hence the better access to fresh air in the 4.2 m test room. This is in line with the results from tests with different ventilation openings.

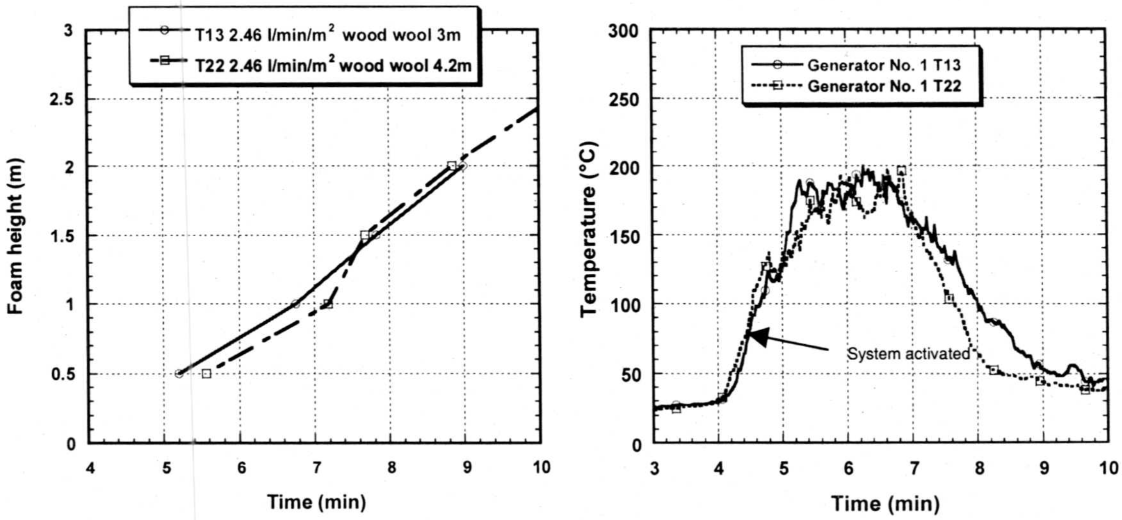

Figure 16 *The average foam height in the test room and temperature at generator No.1 in tests T13 and T22 with ceiling heights.*

In figure 17 one test in the 3 m test room and 68°C activation, Test T05, is compared with one test in the 4.2 m test room, test T21. In test T21 the system was activated when the fire was visually the same size as in test T05.

The results are that the foam build up was slightly better in the 4.2 test room and the temperature was lower. This is also in line with the results from tests with different ventilation openings.

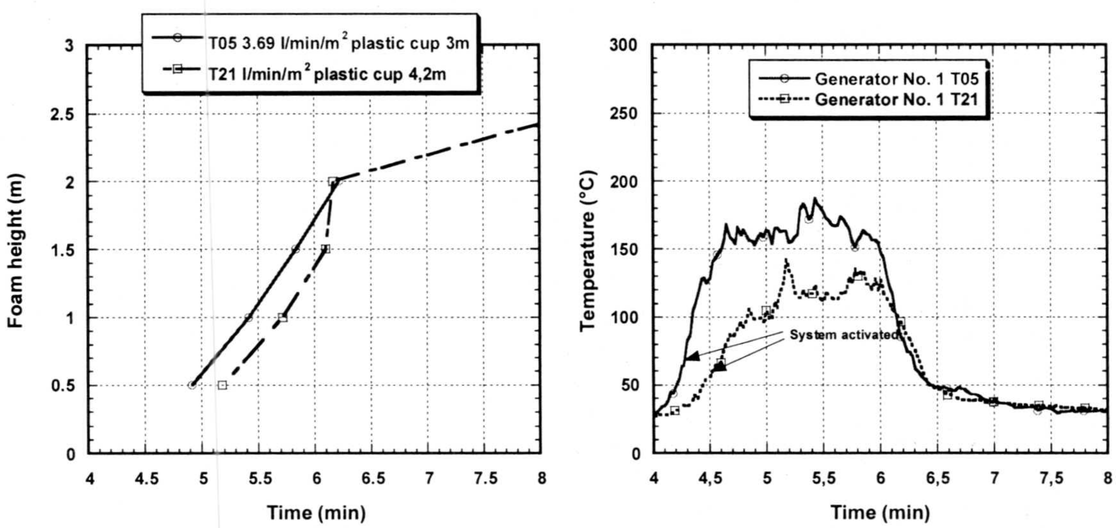

Figure 17 *The average foam height in the test room and temperature at generator No.1 in tests T05 and T21 with ceiling heights.*

6 Conclusions

The aim of the project was to improve and compile knowledge about HIEX foam systems using inside air. The experimental part has been focused on fires in high rack storages. The general conclusion is that the most important parameters for a successful fire fighting performance are the activation criteria and application rate. In a high rack storage where the vertical fire spread is rapid it is very important that the HIEX foam system is activated in an early stage. If the fire is allowed to spread to surrounding racks the probability that the fire will get out of control is impending.

When the temperature at the high-elevated generators rises to 200-400°C the foam generation decreases considerably and at approximately 600°C the foam production stops. The effect of re-circulated steam has not been investigated but this could also be a reason for decreased foam production.

The tests also show that ventilation of the protected area affect the foam generation. If the fire is under ventilated and pyrolysis products are generated, the foam generations decreases even if the temperature at the generators is rather low. When the smoke layer reached the fire source pyrolysis gases increase in amount. The size of the protected enclosure and the degree of ventilation is very important and has to be considered when designing a HIEX foam system using inside air. Tests showed that the size of ventilation openings influenced the foam production and hence the extinguishing ability. However, two different principles for extinguishing can be the result depending on ventilation and the degree of access to fresh air. The first one is that the foam production and foam filling rate is sufficient in order to fill up the room and cover the high rack storages with foam. The second principle for extinguishing appears if the fire is large compared to the size of the protected enclosure and the ventilation is limited. The system could in that case work as a water spray/mist system, meaning that the water will cool the fire and reduce the temperatures in the enclosure.

The cause of the decreased foam production is not completely clear. As discussed above three different phenomenon could be the reason for the decreased foam production; temperature, pyrolysis gases and re-circulated steam. It is therefore suggested to perform tests in small scale in order to define the influence from these factors. The tests should be done with different types of foams to show the importance of the foam concentrate. The tests could be used as a base for developing a small scale test method in order to evaluate foam concentrates for HIEX inside air systems. In existing standards for foam concentrates (EN 1568, ISO 7203 etc.) the ability to produce foam with inside is not considered. The foam concentrate shall be considered as a part of the system and has to be evaluated together.

Some conclusions are summarized below:

- The information about HIEX foam inside air systems is limited. The information is seldom official but is kept in the manufacturers possession.

- Present standards do not specify any design criteria for HIEX inside air system. The paragraph 1-10.9 in NFPA 11a does not specify methods or values for design. The only design criteria is that the application rate shall be adjusted so the influence from combustion gases is compensated.

- Present foam standards, ISO 7203, EN 1568 etc., do not evaluate foam concentrates for the use in HIEX inside air applications.

- Research from the 1960-70th is available about foam destruction caused by smoke. References and tests indicates that pyrolysis gases are able to decrease foam production considerable.

- Limited official information about experience from fires where HIEX foam inside air systems has been used.

- The literature review shows that fires located at low levels, like pool fires, are easy to put out with HIEX foam. The time to activation is not so important in these cases.

- Activation is critical when protecting an enclosure with high rack storages. Tests performed within this project shows that the system has to control the fire before the fire spreads to surrounding rack storages.

- If the air temperature used for foam production is allowed to increase above approximately 300°C the chances to extinguish a fire in rack storage are limited.

- The used foam generators in the test series withstand the heat and no failure was noted.

- It is suggested to perform tests with different foams in small scale in order to define the influence from temperature, pyrolysis gases and re-circulated steam.

The tests in this project have been performed in model scale high rack. It is not possible to make any direct design conclusions for large enclosures. However, the test results can be used to estimate how the investigated parameters should influence the results in full scale if the scale effects are considered.

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Appendix 1 Photos from the tests

Photo No.1 The rack storages in the test enclosure before a test.

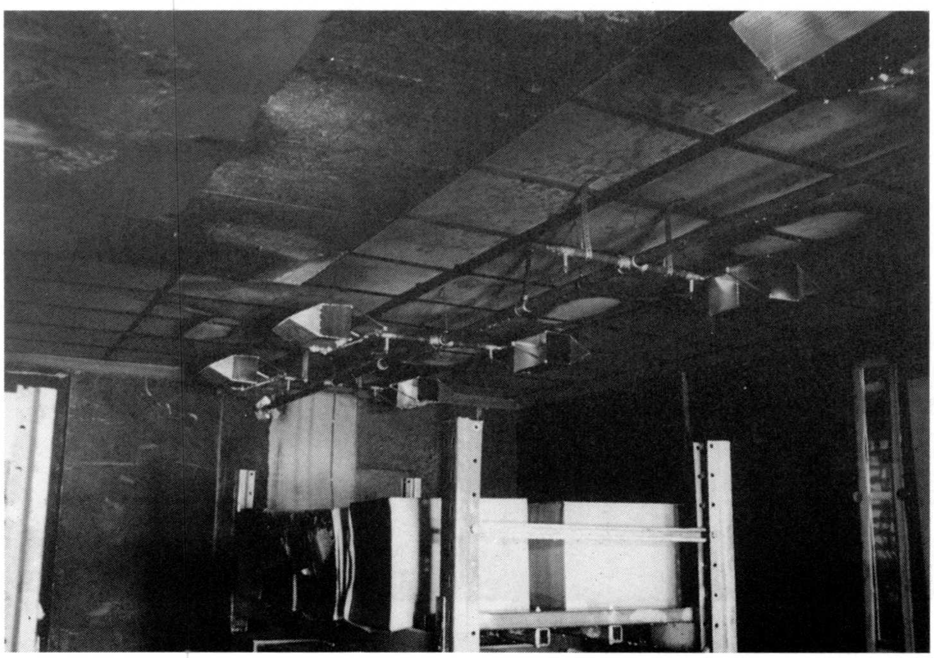

Photo No.2 Foam generators mounted 0.3 m below the ceiling.

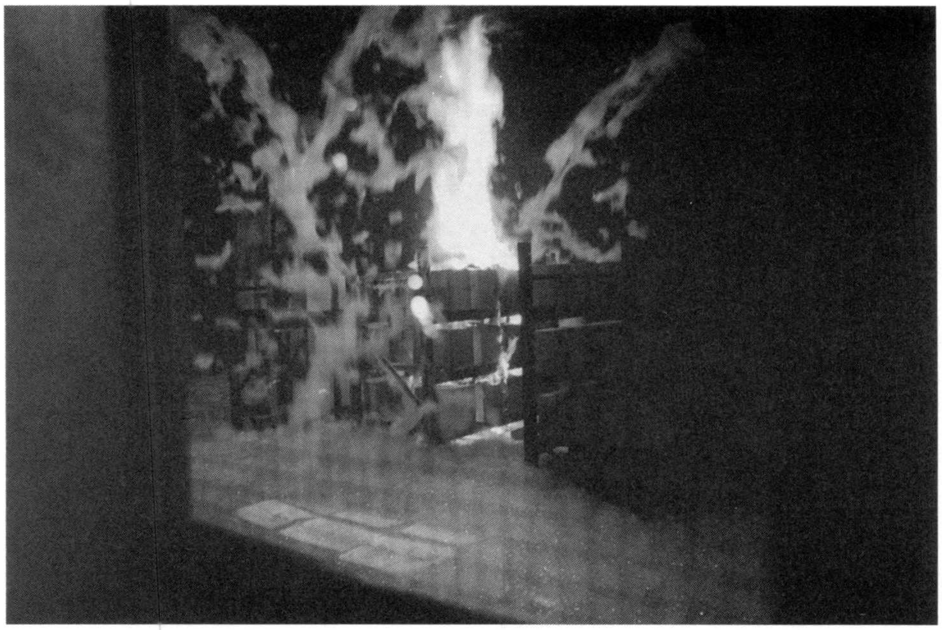

Photo No.3 Picture from test T23. The ceiling height was 4.2 m and the lowest application rate was used, i.e. 8 generators.

Photo No.4 The rack storages after test T06.