

Henry Persson

Evaluation of the RDD-measuring technique

RDD-tests of the CEA and FMRC standard plastic commodities



Abstract

Required Delivered Density (RDD) is a measure of a particular hazard's suppressability and can be defined as the delivered density required to achieve fire suppression. The value of RDD depends on the fire intensity at the time of the application of water. Factory Mutual Research Corporation (FMRC) in USA developed the technique of measuring RDD and has found the test method to be very useful.

The main goal of the project reported here has been to evaluate this technique. A complete RDD measuring equipment similar to that of FMRC has been built at the Swedish National Testing and Research Institute (SP) including a Fire Products Collector (FPC) capable of measuring heat release in the MW range. In total, 23 RDD-tests have been conducted using six different commodities; the FMRC Standard plastic commodity, a commodity used by CEA (Committee European des Assurance), two similar Swedish commodities and two real industrial commodities. In order to study the reproducibility of the method, some identical test commodities have been tested both at FMRC and SP.

The test results show that the RDD-technique provides valuable quantitative measurements with good repeatability and reproducibility. The tests are relatively inexpensive to conduct compared with full-scale tests and therefore this technique may in the future be a base for classification of commodities and storage configurations in sprinkler installation rules. Thereby reliable and cost-effective sprinkler systems may be designed.

Two other measurements developed by FMRC are RTI and ADD which both are sprinkler parameters. Response Time Index (RTI) is an expression of the sensitivity to temperature change of the thermal sensing element of a sprinkler. Actual Delivered Density (ADD) is a measure of the sprinkler distribution pattern and penetration capability in the presence of a fire plume. The influence of these factors are also discussed in the report.

Key words: Required Delivered Density (RDD), water density, sprinkler systems, hazard classification

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**Swedish National Testing and
Research Institute**
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Postal address:
Box 857, S 501 15 BORÅS,
Sweden
Telephone + 46 33 16 50 00
Telex 36252 Testing S
Telefax + 46 33 13 55 02

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1 Foreword

This project has been financed by the Swedish Fire Research Board, BRANDFORSK.

A condition for carrying out the project has also been the very positive contribution from FMRC (Factory Mutual Research Corp) in USA and CEA (Committee European des Assurance) in Europe via LPC (Loss Prevention Council) in UK. They have provided us with test commodities, test results and very valuable technical support during the entire project.

We would also like to thank our Swedish clients who have allowed us to use their data from full-scale tests as well as RDD-tests. Many thanks also to the members of the reference group who have given encouraging support throughout the project and to all my colleagues at SP-Fire Technology, who have contributed to the project.

2 Summary and discussion

The major goal with this project has been to evaluate the RDD (Required Delivered Density) measuring technique. *RDD is a measure of a particular hazard's suppressability and can be defined as the delivered density required to achieve fire suppression. The value of RDD depends on the fire intensity at the time of the application of water.* In theory, the earlier the water is applied to a growing fire, the lower the RDD will be. In practice this is achieved by using quick response sprinklers.

Factory Mutual Research Corporation (FMRC) developed the method in their ESFR project (Early Suppression Fast Response) [1,2,3,4]. The RDD measuring technique enables quantitative measurements of one of the most important input parameters for the design of a sprinkler system, namely the fire hazard classification of goods. Thus various commodities and storage configurations can be evaluated and classified within reasonable costs using relatively small scale tests before the final design of a particular sprinkler system. More efficient and reliable sprinkler systems can thereby be obtained.

So far only FMRC has experience in employing RDD measurements in practice. RDD-tests and comparisons with full-scale tests conducted at FMRC within the ESFR-project are very convincing [10-15]. A test equipment similar to that of FMRC has therefore been built at SP and a series of total 23 RDD-tests have been conducted. Repeatability and reproducibility of the method as well as the correlation between full-scale sprinkler test results and RDD-tests have been studied.

- Several tests at FMRC and SP using similar test commodities and conditions have shown the reproducibility to be very good.
- The FMRC standard plastic commodity and the commodity used by CEA were tested in order to compare the approach in sprinkler research in USA and Europe. Tests were conducted both with the original CEA commodity and a similar commodity supplied by a Swedish source, referred to in this report as CEA and SCEA (Swedish CEA) commodities, respectively. The tests show a large difference in RDD-values; the SCEA commodity required twice the water density of the FMRC commodity. The fire growth rate seemed to be reasonably similar although the fire load (heat content) of the FMRC commodity was 4 to 5 times higher than that of the CEA and SCEA commodities.
- The RDD-results at SP have also been compared with some full-scale tests conducted at LPC (Loss Prevention Council) within the CEA-project [18-20] and full-scale tests conducted at SP, in order to compare the reliability of the RDD-results in practical use. In the tests conducted at SP, three types of test commodities were used, one similar to the SCEA-goods but with larger cartons (Large SCEA) and two types of "real commodities" consisting of unassembled furniture and plastic spare parts for cars, respectively. The limited number of tests are not sufficient for any accurate comparison but the results show in general a reasonable correlation between RDD-tests and full-scale tests.

The test results of the project are briefly summarized and discussed in this chapter. More details and comments can be found in chapter 7.

2.1 RDD-test at SP and FMRC gave similar results

The reproducibility of the RDD-test method was studied by conducting tests under similar conditions both at FMRC and SP. FMRC provided SP with their standard plastic commodity enough to conduct three 3-tiers tests and one 4-tiers test (ESFR RDD-protocol test). SP provided FMRC with the same amount of SCEA goods for the same tests.

The results are very encouraging. The two test series at FMRC and SP resulted in the same standard RDD-brackets [12,15] for the commodities, 14-17.5 mm/min for the 3-tier FMRC commodity and 27-30 mm/min for the 3-tier SCEA commodity.

Another test conducted at SP according to the ESFR RDD-protocol also gave very similar results as a series of tests conducted at FMRC.

It is therefore concluded that the RDD-test method has a good reproducibility, at least if the construction of the water applicator and the FPC (Fire Products Collector) are similar to those available at FMRC and SP. Thus relevant and reliable test data can be obtained and exchanged between laboratories and a universal classification system can be created which will be very useful for designing sprinkler systems in the future.

2.2 RDD-tests correlates well with full-scale tests

The 2-tier and 3-tier high CEA commodity achieved a RDD-value of approximately 13 mm/min and 27 mm/min respectively. This seems to correspond well with the results achieved in the CEA full-scale sprinkler tests at Cardington [18-20]. The 2-tier commodity was in the CEA-tests suppressed using a design density of 17.5 mm/min when the sprinkler clearance was below 4 m. When testing with a 6 m clearance and a design density of 17.5 mm/min, the test failed but succeeded with 30 mm/min to suppress the fire. The 3-tier high storage could not be suppressed at 17.5 mm/min even at 2 m clearance. The results seem logical, as the ADD-value (Actual Delivered Density) from a sprinkler system in practice is more or less below the design density and decreases with increasing clearance.

The influence and the variations of the ADD-value that might occur between various types of sprinklers are shown by two tests also conducted within the CEA-project [19]. The tests were conducted on a 4-tier high CEA commodity using a design density of 40 mm/min. One had a large drop sprinkler and the other an ESFR-sprinkler. The large drop sprinklers failed while the ESFR-sprinklers succeeded in suppressing the fire.

Full scale tests at SP using the Large SCEA, furniture and spare parts commodities in rack storage were all successfully suppressed using ESFR sprinklers. FMRC [17] estimated the ADD-value under these conditions to approximately 42-48 mm/min. The numbers of RDD-tests conducted on these commodities/storage configurations are not sufficient to establish any accurate RDD-values. The obtained results correspond, however, reasonably well with the full-scale tests. The Large SCEA commodity was not suppressed in the RDD-tests using a density of 40 mm/min. The furniture was suppressed using 48 mm/min and the spare parts were suppressed in a test where the density varied from 40 to 60 mm/min.

2.3 RDD-tests give a new dimension of designing reliable sprinkler systems

A general conclusion of the conducted test series is that the *RDD-test provides a lot of valuable information* and most important of all, *in quantitative terms both with respect to the fire behaviour and the suppressability of a certain commodity and storage configuration.*

Data regarding fire behaviour, such as *Heat Release Rate (HRR)* (both total and convective), smoke, toxic gases, etc is very *valuable as input to various types of computer models* for calculating sprinkler release, smoke filling rates, etc.

The *RDD-value* gives the most important figure when designing a sprinkler system for a certain risk, *the minimum water density that must be used to suppress the fire.* In comparison with full-scale sprinkler tests, the test set-up is relatively small consisting of 2 x 2 pallets stored to various heights. In spite of the scale, the test set-up is enough for creating the fire situation where the first sprinklers normally should operate and also suppress the fire.

The results of the RDD-tests conducted at SP correlates well with the results of the full-scale sprinkler tests, as far as it is possible to make any real true comparisons. Full scale tests conducted using a design water density well above the RDD-value shows positive results, while tests conducted just at the RDD-value or below resulted in failures.

A most uncertain parameter in this comparison is the ADD-value (Actual Delivered Density) of the sprinklers used. ADD is a measure of the sprinkler distribution pattern and penetration capability in the presence of a fire plume. So far, this characteristic value is only compulsory to determine according to the rules for ESFR sprinklers. It should be evaluated for other types of sprinklers as well, to make it possible to use the RDD-value in a more general way.

The total released convective heat is a very important part in RDD-tests and is a very useful parameter when establishing the RDD-limit. If the generated heat is put into relation with the water density, the correlation between water density delivered on to the commodities and damage is shown in a very obvious way. Such a correlation is shown in figure 1 where the conducted RDD-tests in this project has been presented by plotting water density versus total generated convective heat. When the water density decreases below the RDD-value for the commodity in question, the fire damage (total released convective heat) increases rapidly. An additional small decrease of the water density results in a situation where the fire can not be controlled or suppressed any more.

As shown in figure 1, the total released heat enables an objective and quantified measurement of the damage. In most full-scale tests, the damage is based on visual observations and expressed in % of the total test set-up which makes it difficult to compare various full-scale tests; a certain damage becomes relatively smaller if a large test set-up is used although the threat from the fire still may be the same. Many commodities, eg the FMRC, furniture or spare parts commodities have a relatively high fire load (heat content of the commodities) compared to eg polystyrene chips. Commodities like the FMRC type can create a very threatening fire and release large amount of heat without the visual fire damage being very large. If the same amount of heat is generated from the chips, this means a much higher visual damage. The fire load of various commodities can be determined by free burn tests of one pallet load, and the differences are very clearly shown in the free burn tests conducted on the various test commodities. The polystyrene chips commodities, CEA, SCEA and Large SCEA, have a fire load of only 20-25 % compared to the FMRC standard plastic commodity.

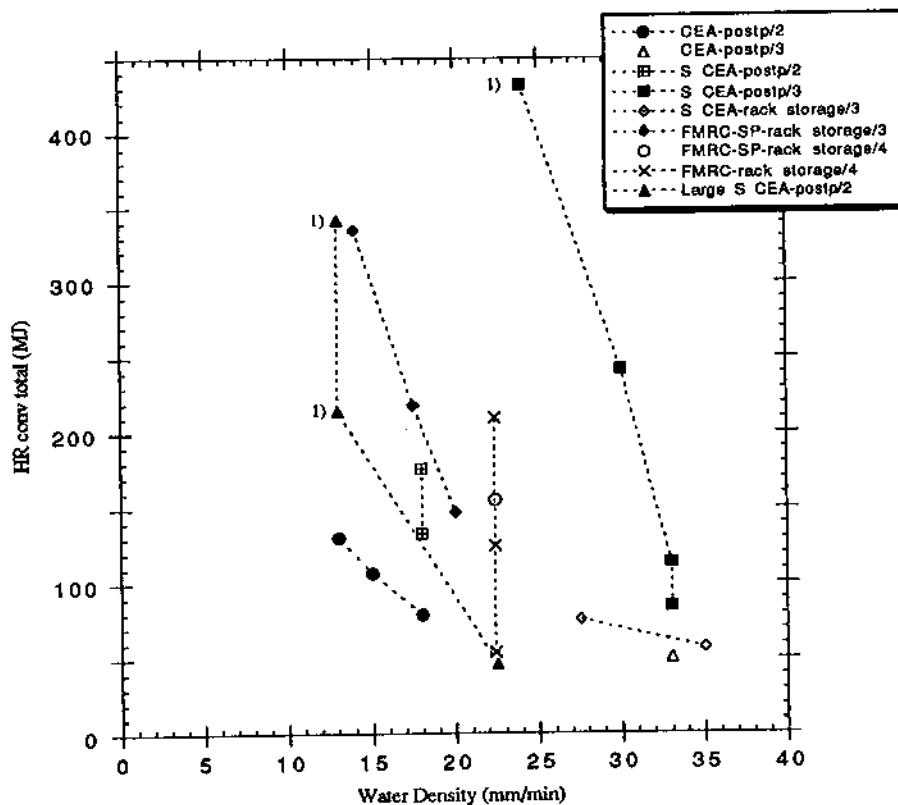


Figure 1 Water density versus total released convective heat for the tested commodities/storage configurations tested in this project. Some results obtained at FMRC (marked as x) are also included for comparison purposes. 1) in the diagram indicates manually terminated tests.

This aspect of fire load is also a matter of concern when these commodities are used in sprinkler research projects where the effects of various sprinkler types, water densities, storage configurations, etc are investigated with full-scale sprinkler tests. If such tests are conducted with commodities like polystyrene chips, the fire load is limited and the fire might be controlled and suppressed due to lack of combustible material rather than high enough water density. The risk for redevelopment of the fire at too low water densities becomes also limited. The FMRC standard plastic commodity is therefore deemed to be the best "test commodity" for simulating "real" conditions for sprinkler systems.

The use of the FPC-equipment (Fire Products Collector) and HRR-measurements gives the possibility to calculate the total heat released and solves the problems of visually estimating the amount of goods consumed by the fire. A quantitative and comparable measurement of the damage can be obtained independently of fire load. This is used in the ESFR concept where the maximum allowed risk that can be protected by an ESFR sprinkler system is expressed by limits on both maximum HRR and total released convective heat during an RDD-test. Also the risk for possible fire jumps from eg one rack to another can be considered by measuring the radiation from the tested commodities. Limits can be set on both the maximum radiation level and the total generated radiative energy. If the tested commodity falls within these limits, it can be protected by an ESFR sprinkler system.

2.4 Existing rules need to be complemented

The tests show that type of commodities and storage height influence considerably. Only two commodities/storage configurations have, however, been tested enough for establishing a RDD-value (or more correct a RDD-bracket, in which the damage starts to increase considerably). These are 3-tier storage of the FMRC- and SCEA commodities where the RDD-bracket is established to 14-17.5 mm/min and 27-30 mm/min, respectively. This means that two commodity/storage configurations which both are considered as "high challenge" in the current classification system have RDD-values differing by about 100 %.

When comparing these values with the existing sprinkler rules in Sweden, RUS 120:3 [6] there is a reason for concern. The SCEA commodity for example, should be classified in storage class L4, which allows the commodity to be stored up to 4.4 m using only ceiling sprinklers. The required design water density is then 17.5 mm/min at 3.0 m and 30.0 mm/min at 4.4 m storage. As the RDD-value might be much lower than the design density, there is no safety margin in the existing rules for this type of commodity.

A question that immediately can be raised is, why is the sprinkler statistics so good when the required water densities seem to have no safety margin? The answer to this can actually be found by a closer look in the statistics. Sprinkler statistics presented by NFPA [8] covering fires from 1970 to 1974 show that for wet systems about 40 % is suppressed by 1 sprinkler and about 70 % is suppressed with 4 sprinklers operating. Only in about 5 % of the fires, more than 20-40 sprinklers which can be considered as a normal design area have been operating.

The design water density which is referred to in most sprinkler rules is, however, calculated assuming that all sprinklers within the design area are open. In most cases the water pressure decreases when the water flow increases as shown in figure 2. Therefore the first sprinklers operating will deliver a water density far above the design density. This will compensate for the difference between design density and ADD and probably often more than that. As an example, a hydraulic analysis of a real sprinkler installation made by Gustavsson [21] is shown in table 1. The data for the installation in this example are as follows:

The design density is 30 mm/min, the design area 6.75 m² per sprinkler and there are 45 sprinklers within the design area. The system is a grid system, the main line 200 mm, distribution pipes 100 mm and 150 mm, ranges 41.8 mm with 6 sprinklers per range. The K-factor is 11.5 (l/min,kPa⁻²). The height difference between the pump and sprinklers are 13 m. The pump is supplied with water from a tank.

Table 1. Calculated water pressure, total flow rate and water density in a certain installation when 45 and 4 sprinklers are operating, respectively [21].

Numbers of operating sprinklers	Pressure at pump (bar)	Pressure at sprinkler (bar)	Total flow rate (l/min)	Water density (mm/min)
45	8.1	3.1	9436	30
4	10.0	8.0	1296	48

The water density with four operating sprinklers is 60 % higher than the design water density stipulated by the rules. As the thrust from the sprinkler spray often increases with increasing water pressure it is possible that the ADD-value from the sprinklers increase with even more than 60 %.

This is a possible reason for the very good statistics, which we mostly get "free of charge" in most installations. If all systems had been designed giving a constant density independent of the number of operating sprinklers, the sprinkler records would probably not be as good.

A reliable sprinkler system has to be designed to control and suppress the fire in the initial stage which means that RDD- and ADD values have to be considered. In practice, this means that one must require a certain water pressure also when only a few sprinklers are operating and the ADD-values of the sprinklers have to be known.

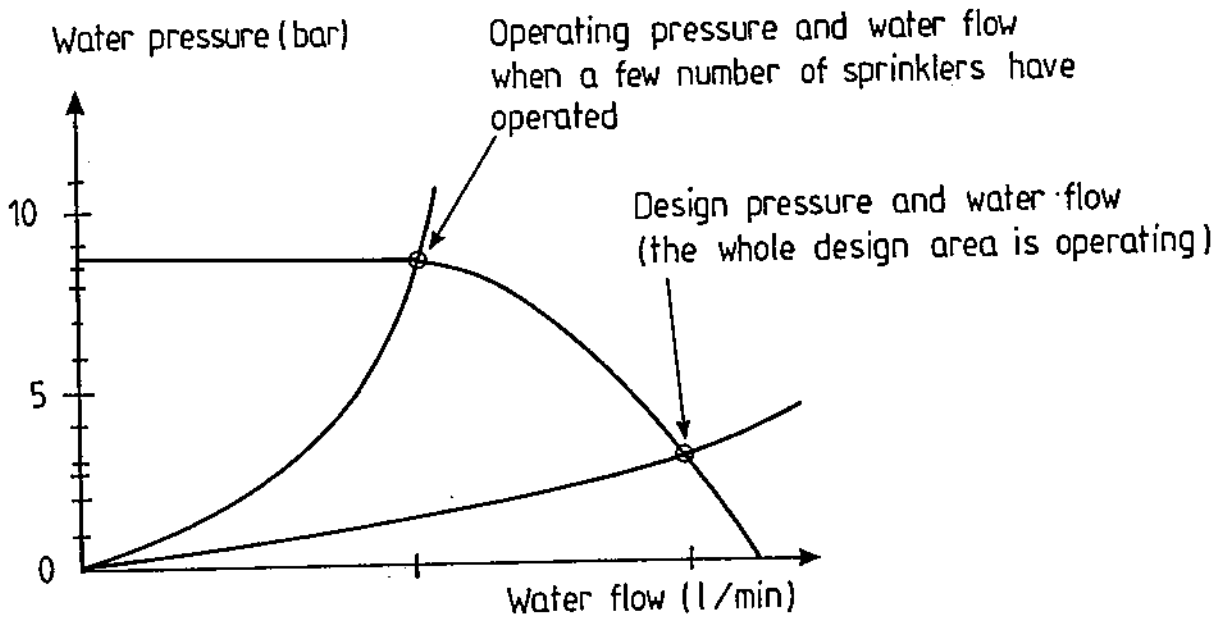


Figure 2 Generalized pressure-flow rate diagram showing the difference between design and operating pressure when only a limited number of sprinklers operate.

2.5 Influences of commodities, storage height and number of tiers needs to be further investigated

The tests in this project have shown that the RDD-value varies considerably depending on type of commodities and the configurations can influence. It is not clear whether these differences fully correspond to the classification criteria and requirements in the existing sprinkler rules [5, 6]. Further tests should be made to study various types of commodity/storage configurations classified in the different existing classes to see whether this classification is reasonable or not. In many cases the present classification is made on a very subjective basis, resulting in that the same commodity might be put into various classes depending on who makes the judgement.

Such RDD-tests should be used to validate the correlation between full-scale sprinkler tests and the RDD-value. The ADD-value has to be known on the sprinklers used, otherwise tests can not be compared. As the experience grows, the number of full-scale tests might be reduced to verify only such materials and storage configurations which create trouble when performing normal RDD-tests. This might be solid piled storage which very soon collapses, higher storage of very fast burning materials such as the polystyrene chips, etc.

3 Introduction;

During the last 10 years, there has been an intensive research in the sprinkler area. In USA, FMRC has developed the ESFR-sprinkler, and in Europe, CEA has sponsored several sprinkler projects where a great number of large scale tests have been conducted.

The development of the ESFR sprinkler has really introduced new ideas and concepts in to the sprinkler technology, such as early suppression, ADD and RDD. The basic ESFR concept is, if sufficient water can be delivered on to the fire in the early stages of fire growth, the fire will be suppressed rather than controlled. In-rack sprinklers may therefore in many cases not be necessary. There are three key parameters of the ESFR approach; [1, 2, 3, 4]

- 1) *The RTI (Respons Time Index)* is a measurable expression of the responsiveness to temperature change of the thermal sensing element of a sprinkler. The more responsive the element is to temperature changes, the lower the RTI value. Depending on RTI value, sprinkler temperature rating and sprinkler location, the sprinkler will operate when the fire reaches a certain burning intensity. This corresponds to a certain convective HRR (heat release rate) and is used in the RDD-measurements to start the water application.
- 2) *The ADD (Actual Delivered Density)* is the rate at which water is actually deposited from the operating sprinklers onto the top horizontal surface of a burning combustible array. ADD is a measure of the sprinkler distribution pattern and penetration capability in the presence of a fire plume. As the delay in sprinkler activation lengthens, the fire size increases and the ADD decreases. ADD is a function of fire plume velocity, the drop momentum and size, and the distance the drops must travel.
- 3) *The RDD (Required Delivered Density)* is the measure of a particular hazard's suppressability. RDD can be defined as the delivered density required to achieve fire suppression. The value of RDD depends on the fire size at the time of the application of water.

The generalized ADD-RDD concept is that early suppression of the fire is expected when ADD is greater than RDD as shown in figure 3.

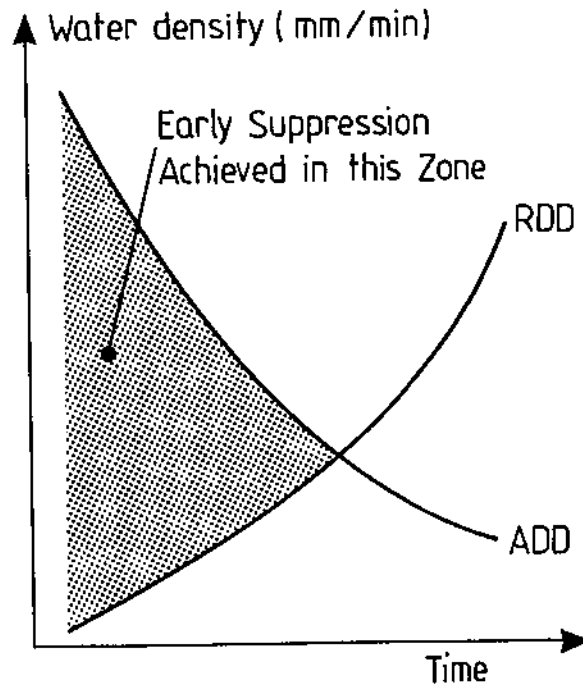


Figure 3. The principal requirement for early suppression of a fire is that the water delivered by the sprinkler to the burning commodity (ADD) must be greater than the water density needed to suppress the commodity (RDD).

Based on this technique, a standard for ESFR-sprinklers [7] has been issued and several ESFR-sprinklers are now available on the market. They typically have high k-factors of approximately 20 (l/min, kPa⁻²), and a low RTI-value of approximately 30 (m^{1/2} s^{1/2}). To achieve the specified ADD-values, the sprinklers produce special spray pattern with large drops. The sprinklers might be used to protect various commodities/storage configurations up to 7.6 m with a ceiling height of max 9.1 m. The design area used is 12 sprinklers [4, 5, 9]. The requirement for the commodity/storage configuration is that their RDD-value and other parameters measured in the RDD-test must not exceed certain values (ESFR, RDD-test protocol).

In the CEA-projects all tests are performed as full-scale tests. The main object with the projects has been to see if more cost effective sprinkler systems could be designed using new types of sprinklers, by evaluating the main factors affecting sprinkler performance. Sprinklers having k-factors, approximately 8-11.5-16 (l/min kPa⁻²), have mainly been used. Influence of parameters such as RTI-value, drop size from the sprinkler, storage height, clearance, wet or dry system, etc have been studied. Recently, one test using an ESFR-sprinkler has also been conducted.

If the test results show that an increase in efficiency can be achieved, this would mean that existing rules could be revised. It also could enable retrofitting of existing installations without too high costs.

The test commodity used by CEA is polystyrene chips packed in corrugated cartons loaded on wood pallets and stored in postpallet system. Some tests have also been conducted using solid-piled storage.

A great advantage in the ESFR-philosophy is the use of the RDD-measuring technique. Until recently the only available RDD-test facility has been at FMRC and they have also been the only laboratory having practical experience of the method. In order to get our own experience of the method and also to be able to offer these tests to our clients, SP-Fire Technology has built a RDD-test equipment similar to that of FMRC.

The major goal of this project has been to evaluate the RDD-measuring technique by;

- studying the reproducibility by comparison tests with FMRC
- studying the fire behaviour and suppressability of the commodities and storage configurations that CEA uses, resulting in the possibility to make a better and more accurate technical comparison between the results achieved within the research projects conducted by FMRC and CEA respectively.
- studying the reliability of the RDD-results in practical use by comparison of RDD-results and results from full-scale tests.

The project was made possible thanks to CEA and FMRC, who have provided us with sufficient test commodities for approximately four tests each. In order to study the reproducibility of the method we have also provided FMRC with test commodities similar to the CEA commodities, referred to as SCEA ("Swedish CEA") commodity". This commodity is made from material of Swedish origin but is otherwise almost similar to the original CEA commodity. From the economic viewpoint, the SCEA commodity had to be used to a large extent in this project in order to be able to perform the necessary RDD-tests.

Comparison with full-scale tests have also been possible to perform on some other commodities and storage configurations provided by some Swedish companies. SP has on behalf of these companies performed some full-scale sprinkler tests and RDD-tests with furniture, spare parts for cars and polystyrene chips in large corrugated cartons.

Totally, 23 RDD-tests have been performed and the results are presented in this report.

4 Test equipment

The RDD-tests were conducted in the fire hall at SP-Fire Technology. The dimension of the fire hall is 18 m by 22 m with a maximum height of 20 m. A principal layout of the fire hall, FPC (Fire Products Collector) and RDD-test set-up with the water applicator placed above the test commodities is shown in figure.4.

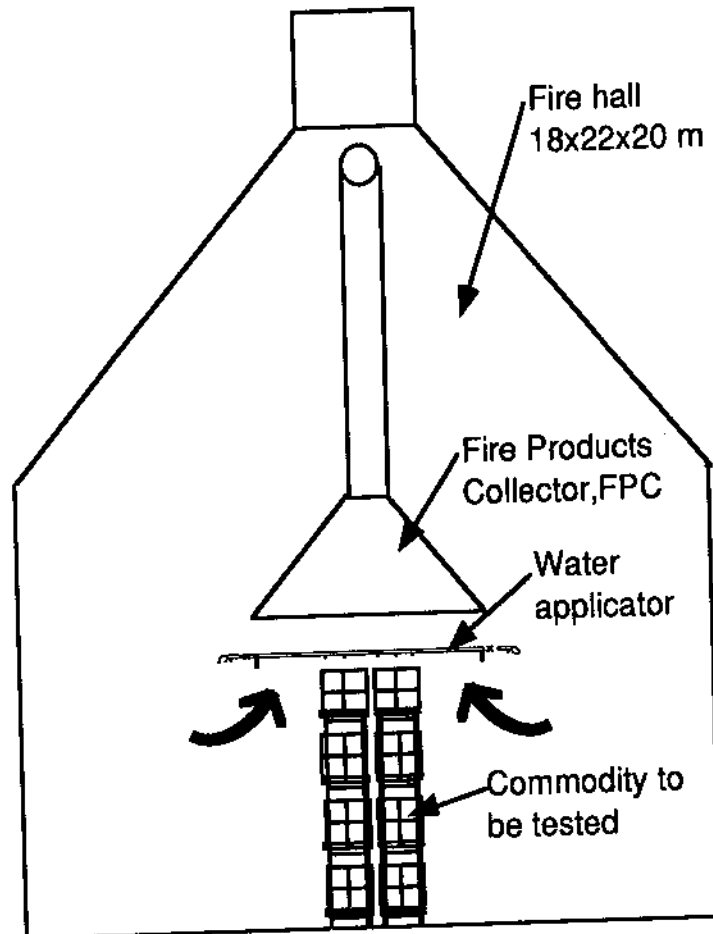


Figure 4. A principle sketch of the test set-up in the fire hall at SP-Fire Technology. The commodities with the water applicator on top were placed below the Fire Products Collector.

4.1 RDD-test equipment

During an RDD-test, both fire behaviour and suppressability is tested. The fire behaviour is achieved by measuring the heat release rate from the fire using a large FPC. When the fire has developed to such an intensity that the generated HRR would have caused a sprinkler to operate, a special water applicator is activated. This applies an even water density on top of the fuel array, simulating the water coming from the sprinklers in a real situation. Continuing measurements of the heat release rate during the water application gives information of the suppressability of the tested commodity and a principle example of HRR-achieved using various water density close to the RDD-value for the commodity/storage configuration is shown in figure 5. A water density below the RDD-value results in redevelopment of the fire, a slightly higher density controls and suppresses the fire but generating quite a lot of released heat. When reaching the RDD-value, the suppression is more definite and the released heat during the extinguishment is below certain stated limits.

Below is a brief description of the equipment, test set-up and test procedure. As most of this is similar to what is used at FMRC, more detailed information can be found in FMRC report J.L.ON1JO.RA(1) [14].

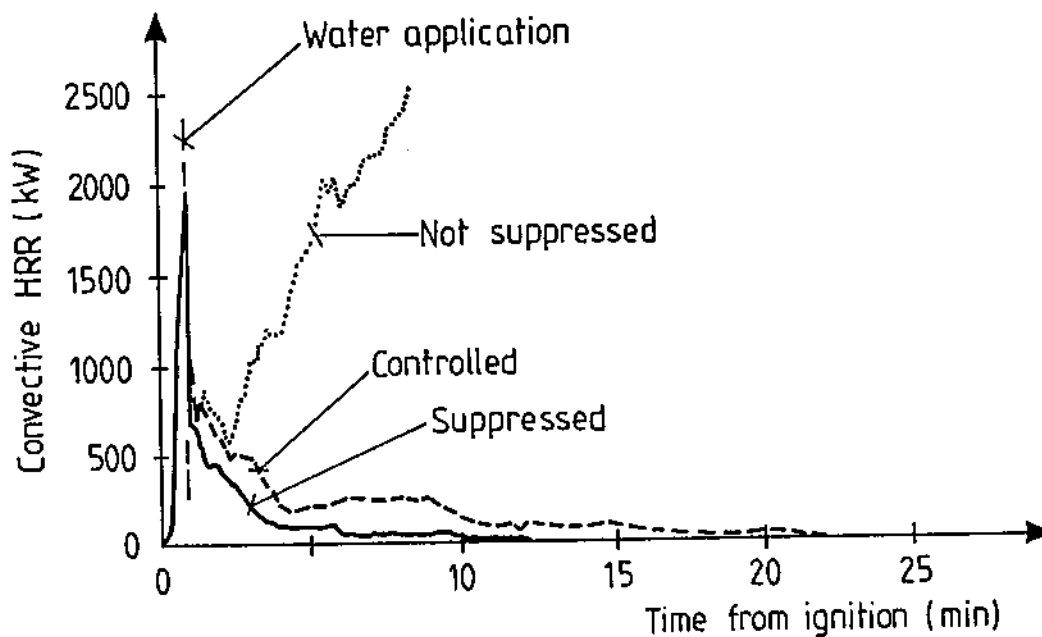


Figure 5. The figure is in principle showing achieved HRR during three RDD-tests using various water densities below and at the RDD-value for a certain commodity/storage configuration.

4.2 FPC (Fire Products Collector)

The FPC is a large hood connected to an evacuation system capable of collecting all the combustion gases produced by the fire. The hood is 6 m in diameter with its lower rim 8 m above the floor as shown in figure 4. The FPC is designed similar to the FPC at FMRC, both in size and evacuation capacity [16]. In the duct to the evacuation system, measurements of gas temperature and velocity and the generation of gaseous species such as CO_2 , CO and the depletion of O_2 is made. The generation of smoke is also measured with a photocell equipment. Based on these measurements both the convective and total heat release rate can be calculated. In the RDD-measurements, it is mainly the convective heat release rate that is considered, as it is the convective heat which mainly causes the sprinklers to operate.

4.3 RDD-water applicator

The applicator consists of six parallel, double-jacketed, steelpipes fitted with six spray nozzles along each pipe, forming a matrix of nozzles 450 mm apart, see figure 6. The nozzles produce a full-cone, wide angle spray, resulting in an even water density over a maximum area of 2.7 m x 2.7 m. When a commodity stored on normal European wood pallets (1.2 m x 0.8 m) is tested, only four of the pipes are used while the two outer pipes are disconnected.

The suppression water is fed from both ends into the pipe. In order to reduce the fill-up time as much as possible an air relief device is installed at the midpoint of the pipes. This allows the air in the pipes to bleed, but shuts off as soon as the pipes are filled with water. In order to reduce the fill-up time even more, a special charge line is also connected. This is controlled with a time relay and is shut off at the same moment as the pipes are filled with water. This "charge time" has to be adjusted for each flow rate. The feeding line is equipped with a flow meter and a pressure transducer in order to adjust the flow rate corresponding to the desired water density.

In order to protect the applicator from the flames, the applicator is water cooled in the annular area of the double jacketed pipes. The cooling water is feeded from one end and discharged through the other.

The water applicator has been calibrated for the various storage configurations and the result is presented in Annex B. The water densities in this report refers to the true densities based on this calibration.

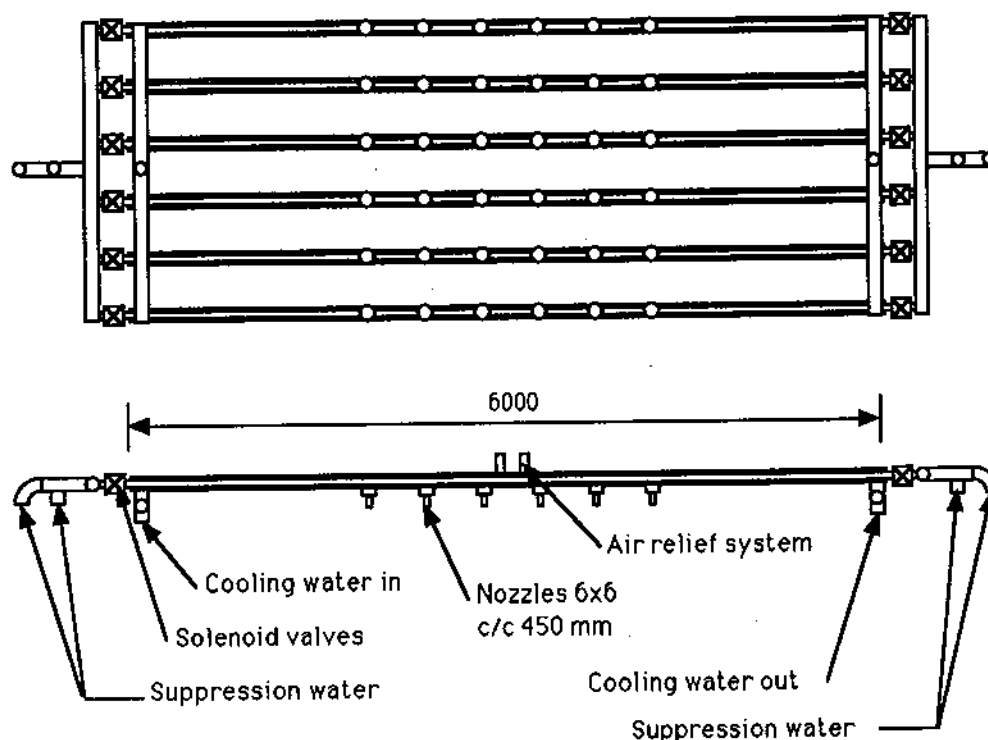


Figure 6. The desired water density is achieved using a water applicator giving an even water distribution on top of the fuel array and the figure shows the principal design of the applicator used at SP-Fire Technology.

Two types of spray nozzles have been used, both manufactured by Spraying Systems Company;

- Model 1/8 GG 5.6W for water densities below 25 mm/min
- Model 1/4 HH 14 W for water densities above 25 mm/min

The construction of the applicator is basically identical with the one FMRC uses. However, the distances between the double-jacketed pipes and the number of nozzles has primarily been designed to fit European pallets and storage configurations. This new design has been constructed with guidance from FMRC [17].

4.4 Ignition source

As ignition source, four igniters were used made of pieces of insulating fibre board, 75 mm in diameter and 75 mm long. Each igniter was soaked in 120 ml of heptane and wrapped in a polyethylene bag. The igniters were placed near the centre flue space at the bottom of the pallet loads of the lowest tier.

5 Test goods and storage configurations

Basically three types of test commodities have been used;

- FMRC Standard plastic commodity
- CEA standard commodity
- SCEA (Swedish CEA) commodity

The FMRC and CEA commodities were supplied directly from FMRC and LPC enough for four RDD-tests of each. In order to study the influence of storage height, repeatability of the method, etc, more tests were necessary to perform. A test commodity similar to the CEA commodity was therefore used. For the sake of convenience and from the economic aspect, this material was bought from a Swedish source and this commodity is referred to as SCEA in this report. The four tests conducted with the FMRC commodity was judged to be sufficient since a lot of comparison data is available from FMRC.

5.1 FMRC Standard plastic commodity

The commodity consisted of polystyrene cups packaged in compartmented, single-wall corrugated cartons. The average weight of each carton was 6850 gr, where 4125 was polystyrene and 2725 corrugated carton. The size of each carton was 530 mm x 530 mm x 510 mm high and contained 125 compartments (with one plastic cup in each compartment) in a 5 x 5 x 5 array.

The cartons were placed on a wood pallet and each pallet load consisted of 8 cartons placed in a 2 x 2 x 2 array (see figure 7).

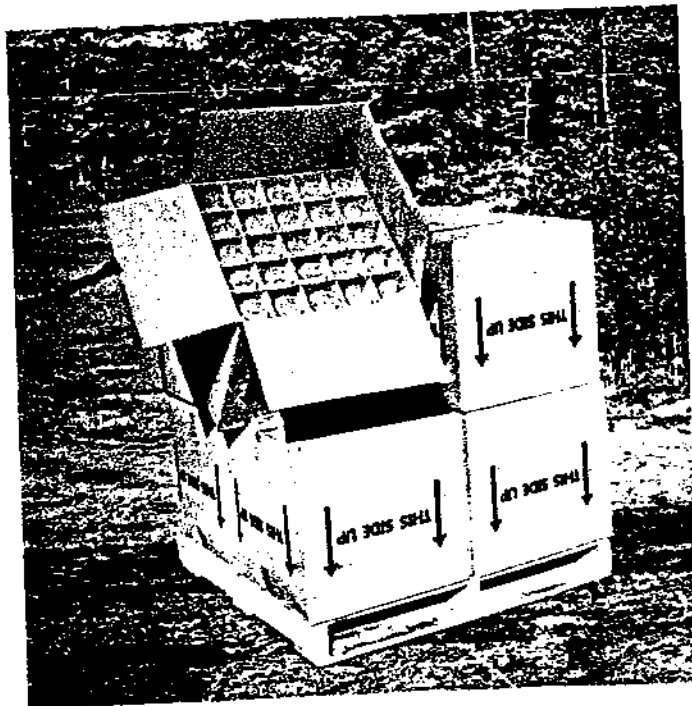


Figure 7. The FMRC standard plastic commodity consists of 125 polystyrene cups packed in a compartmented carton. The cartons are placed on a wood pallet, eight on each pallet. (Figure from ref [14]).

The fuel array tested was two-pallet loads wide, two-pallet loads deep and three or four-pallet loads high. A double row steel rack was used to hold the pallets, and the flue spaces between the pallets was 150 mm. A principal sketch of the test set-up is shown in figure 8.

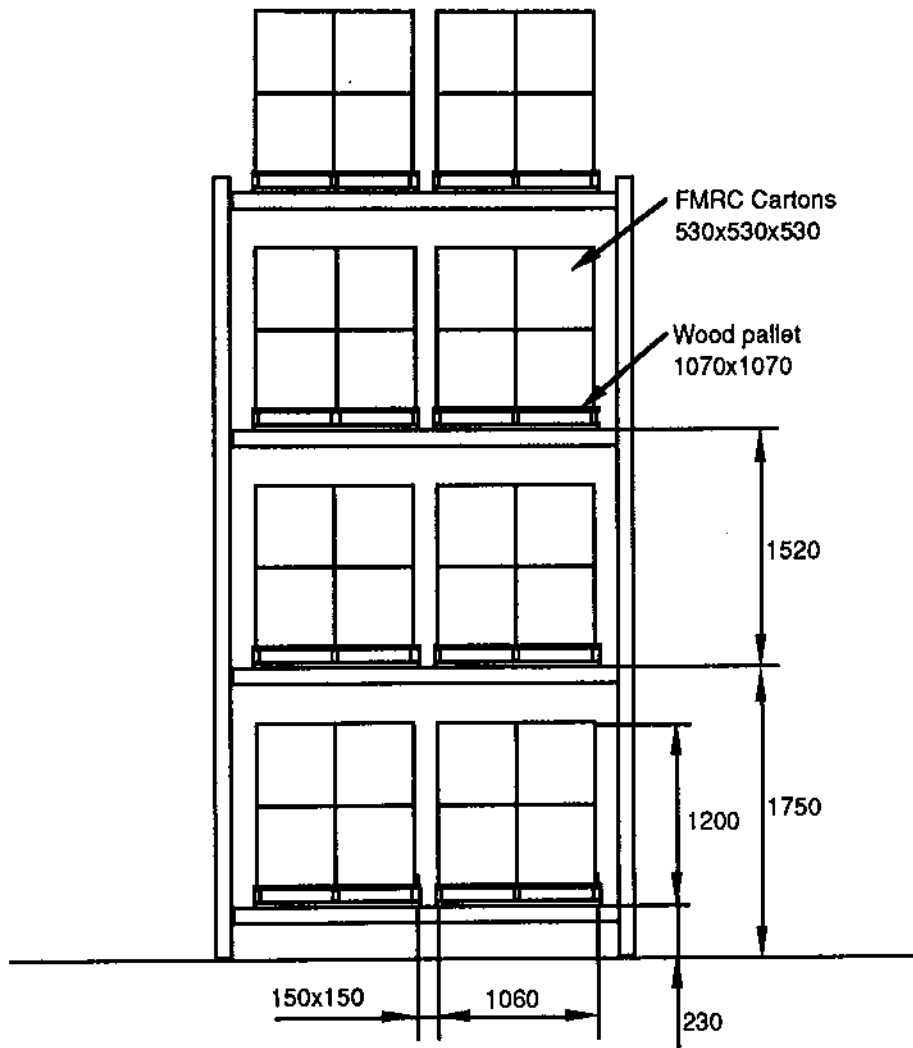


Figure 8. Arrangement of FMRC standard plastic commodity in a 4-tier rack storage configuration which is also referred to as ESFR RDD-test protocol.

5.2 CEA standard commodity

The CEA standard commodity consisted of polystyrene chips packaged in single-wall corrugated cartons. The cartons were filled completely with chips and the average weight of each carton was 1145 gr. The weight of the corrugated carton was 805 gr and the chips 340 gr (filling tolerance ± 15 gr). The size of each carton was 450 mm x 550 mm x 370 mm. The cartons were placed on a wood pallet and each pallet load consisted of 12 cartons placed in a 2 x 2 x 3 array.

The fuel array tested was two-pallet loads wide, two-pallet loads deep and two or three pallet loads high. A so called post pallet system was used to hold the pallets. The post pallets can be placed on top of each other and then form a storage configuration nearly like a rack storage system. The post pallets were placed close to each other resulting in flue spaces between the pallets of approximately 450 mm along the short side of the pallets and approximately 150 mm along the long side of the pallets. In order to avoid the cartons to topple from the pallets during the test, the cartons on the second and third tier were supported with a wire around each layer of cartons. A principal sketch of the test set-up is shown in figure 9.

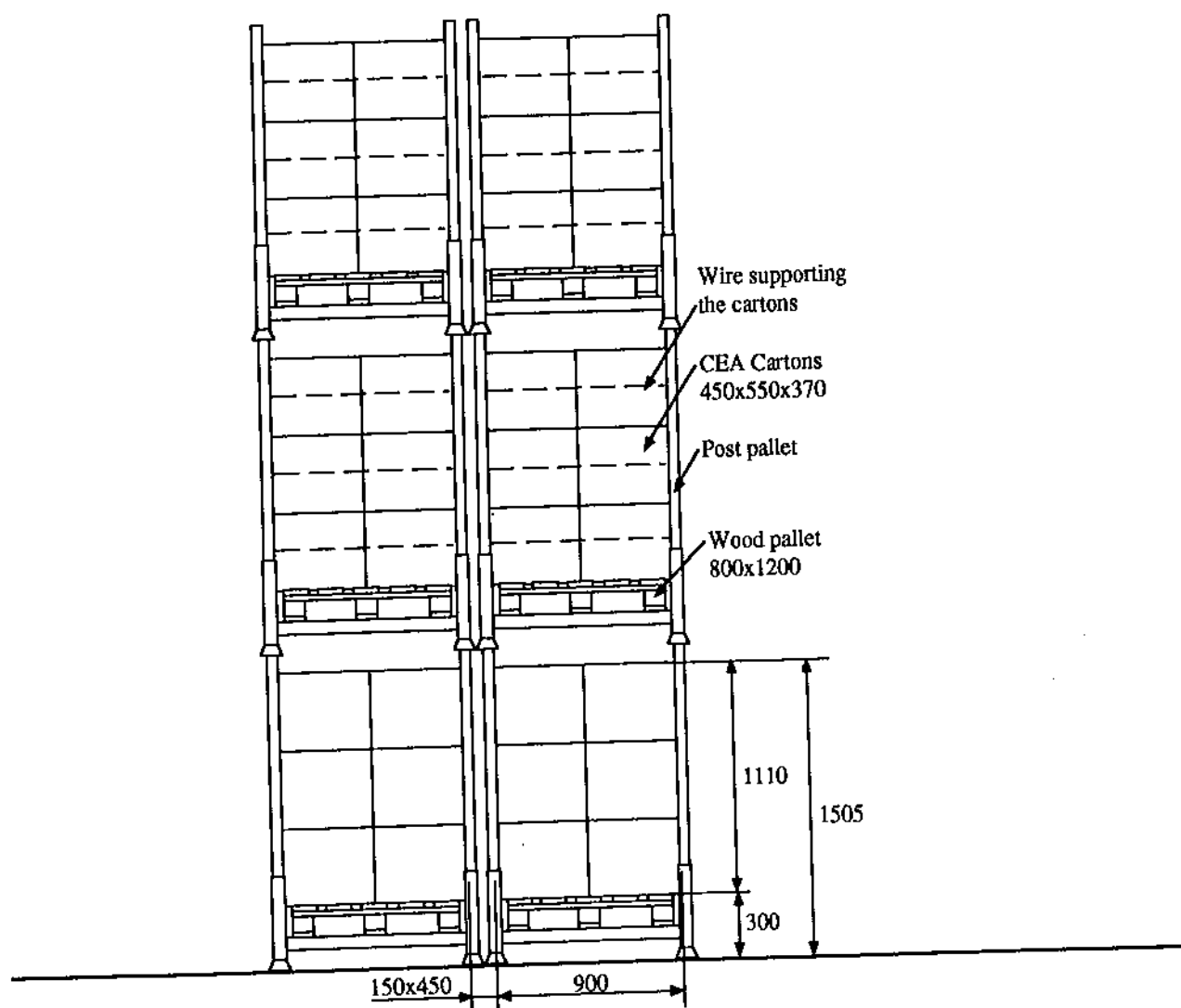


Figure 9. Arrangement of CEA standard plastic commodity in a 3-tier post pallet storage configuration. Because of the post pallet system, the flue spaces become larger than in a rack storage.

5.3 Swedish CEA (SCEA) standard commodity

This commodity was very similar to the original CEA commodity and consisted of polystyrene chips packaged in single-wall corrugated cartons. The cartons were filled completely with chips and the average weight of each carton was 1120 gr. The weight of the corrugated carton was 700 gr and the chips 420 gr (filling tolerance ± 15 gr). The chips had another shape compared to the CEA-chips and also the size of each carton was slightly different to the original CEA cartons, 380 mm x 570 mm x 380 mm. The cartons were placed on a wood pallet and each pallet load consisted of 12 cartons placed in a 2 x 2 x 3 array. A principal sketch of the test set-up is shown in figure 10.

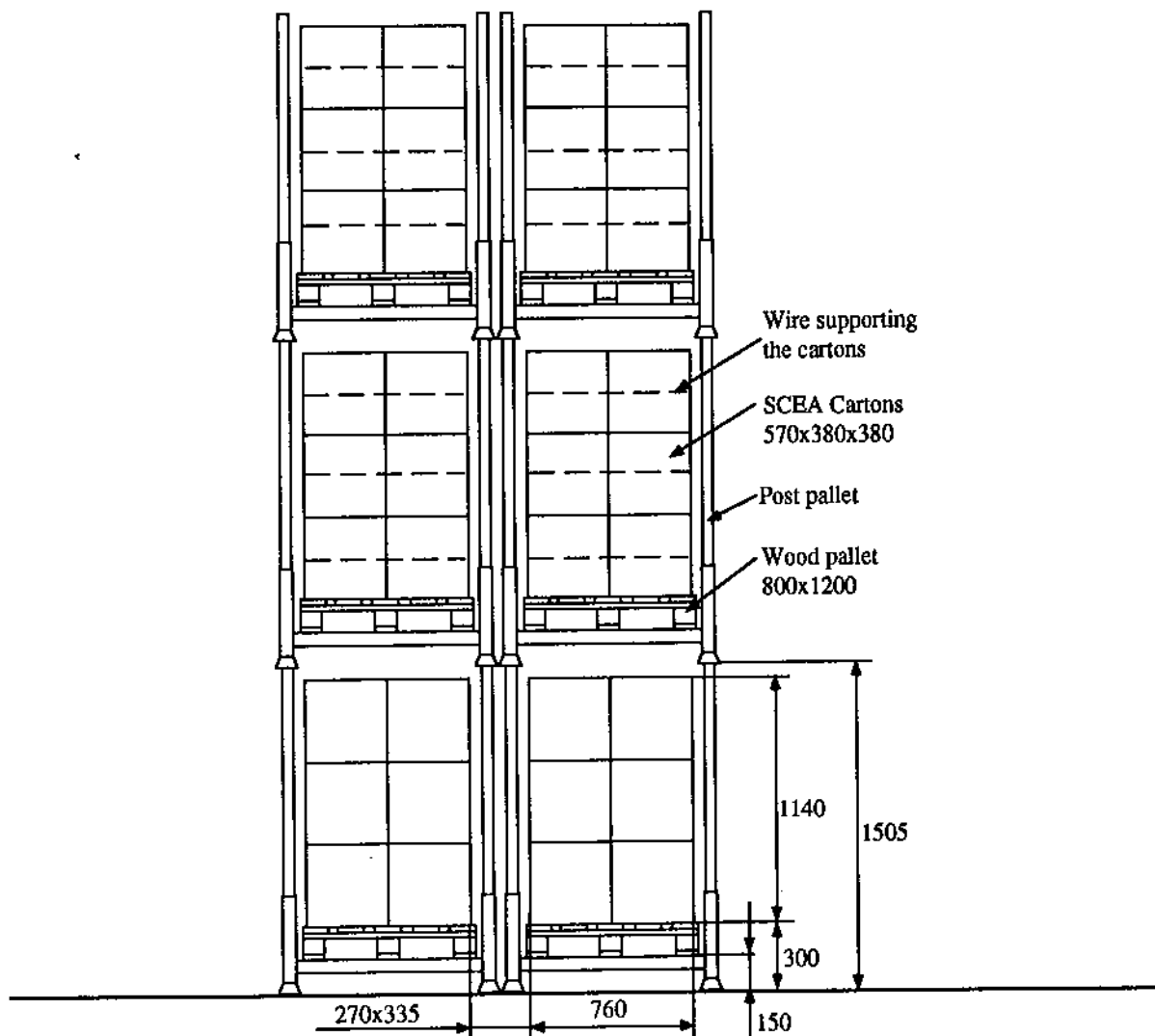


Figure 10. Arrangement of SCEA plastic commodity in a 3-tier post pallet storage configuration. Because of the different size of cartons, the flue spaces were slightly different to the CEA configuration. The rack storage configuration was the same except that the flue spaces were more narrow.

The fuel array tested was two-pallet loads wide, two-pallet loads deep and two or three-pallet loads high. Both a normal rack storage system and a so called post pallet system was used to hold the pallets. When the post pallets were used the flue spaces between the pallets were approximately 335 mm along the short side of the pallets and approximately 270 mm along the long side of the pallets. In the tests using rack storage, the flue spaces were 200 mm and 100 mm respectively. The cartons were supported by a wire in the same way as described in 5.2.

5.4 Other tested goods and storage configurations

Some tests has also been conducted using other commodities and storage configurations as they had been used in full-scale sprinkler tests. The sprinkler tests were conducted below a 10 m x 10 m suspended ceiling inside the fire hall at SP-Fire Technology. The sprinkler spacing was 3 m x 3 m in all tests. The following commodities have been tested:

- *"Large SCEA"* consisting of polystyrene chips packaged in single-wall corrugated cartons. The cartons were filled to 75-80 % of its volume and the average weight of each carton was 2690 gr. The weight of the corrugated carton was 1470 gr and the chips 1220 gr (filling tolerance appr ± 50 gr). The quality of the chips and cartons were identical with the SCEA goods. The only difference to the SCEA commodity was the size of each carton, which was approximately 800 mm x 600 mm x 500 mm.

The cartons were placed on a wood pallet and each pallet load consisted of 4 cartons placed in a 1 x 2 x 2 array. RDD-tests were conducted both in rack storage and post pallets configuration. The full-scale sprinkler tests were conducted using a rack storage. In these tests the storage height was 6.5 m consisting of 4 tiers and the ceiling height was 8.2 m.

- *Unassembled furniture* consisting of solid wood or fibre board, mostly packed in single-wall corrugated cartons. Some commodities also consisted of expanded and unexpanded plastic materials, such as chairs and cushions for sofas etc. The commodities were classified as L3 and L4 respectively according to the Swedish sprinkler rules RUS 120:3 [6].

The commodities were stored on wood pallets in a rack storage, 4 tiers high corresponding to a storage height of 6.0 m. The ceiling height in the sprinkler tests was 7.2 m.

- *Spare parts for cars* consisting of expanded and unexpanded plastic items stored on a wood pallet with pallet rims of wood but without any cover on the top. The pallets were stored in a rack storage 5 tiers high corresponding to a storage height of 6.5 m. The ceiling height was 8.2 m.

6 Test procedure

Before an actual RDD-test is conducted, the flow rate from the water applicator has to be adjusted to achieve the correct water density. Also the charge time has to be adjusted to get as short fill-up time as possible.

When the flow rate has been adjusted, the sprays are visually examined to ensure that the nozzles are free from blockage and that the air-relief valves are working properly. The water is then turned off. When the nozzles are free from dripping, the test commodities and the igniters are put in place in the steel racket.

When the commodities are in place the FPC-system is started and calibrated. The measuring is then started to achieve baseline signals from the instruments, in this project 4:00 min before the fuel array is ignited. Measurements are made every 3 seconds, and for every measurement the convective HRR is calculated and shown on the computer screen.

When the convective HRR reaches a predetermined value, the water applicator is activated manually. This HRR value corresponds to the heat release rate where a sprinkler with a certain RTI value, temperature rating and location would have operated in a real sprinkler installation. The data acquisition and the calculation of the convective heat release rate continues until the test is terminated.

7 Test results

Totally, 23 RDD-tests have been conducted, four with the FMRC-commodity, 5 with the original CEA-commodity, 10 with the SCEA-commodity and 4 tests with other commodities. During three tests, the commodities fell down or collapsed to such an extent that these tests have been rejected and not reported. One of these tests was simulating approximately 4 m solid piled storage of the CEA commodity.

Below is a presentation of the main results and conclusions regarding reproducibility of the method, comparison of the various commodities/storage configurations and correlation with full-scale tests.

A complete summary of the results is given in Table A1 and A2 in Annex A.

7.1 Results of comparison tests with FMRC

In order to study the repeatability of the test method, some identical tests have been performed both at FMRC and SP, using both FMRC standard plastic commodity and the SCEA commodity.

In this test series, SP has been conducting four tests with the FMRC-commodity, one ESFR RDD-protocol-test (4-tier high storage), three tests with a 3-tier high storage and three tests with a 3-tier high post pallet storage using the SCEA-commodity.

FMRC conducted four tests with SCEA-commodity, one as a RDD-protocol test and three with a 3-tier high storage using a post pallet configuration. For comparison purposes, test data from various tests with the FMRC-commodity has been supplied by FMRC [12,14].

7.1.1 ESFR RDD protocol test

The convective HRR from the ESFR RDD-protocol test conducted at SP and for comparison, one of three similar tests conducted at FMRC [14] are shown in figure 11. As can be seen from the HRR-curves and the results summarized in table 2, the results of the tests conducted at SP are quite similar to the FMRC-tests, especially test 1.

The possibility for fire jumps to adjacent arrays, measured with two radiometers at 6.25 m distance also gave similar results as achieved by FMRC, see figure 12. As noticed in the tests at FMRC, the flame radiation was very sensitive to the flame location during the test and it did not always closely follow the convective HRR. To really evaluate the risks of the radiation, the irradiance level ought to be measured on all four sides of the test array to avoid uncertain results due to flame location.

Table 2. Comparison of ESFR RDD-protocol tests conducted at FMRC [14] and SP. Whether ESFR sprinklers are capable of protecting a certain risk is evaluated by a similar RDD-test using the commodity in question. The results have to be within the specified limits which are based on the three FMRC tests.

Test org/ test No	FMRC 1	FMRC 2	FMRC 3	SP Z09	RDD-limits for ESFR- sprinklers
Water density (mm/min)	22.4	22.4	22.4	22.4	22.4
HRR at water appl (kW)	2021	2533	2489	2150	
HRR max (kW)	2400	3172	2673	2270	3500
Conv heat released (MJ)	125	54	210	156	270
Radiation max (kW/m ²)	1.03	0.5	0.92	0.95	1.35
Radiation, total released (kJ/m ²)	210	110	430	195	560
Max link temp 2nd ring (°C)	51.4	58	55	*	61

* Not calculated

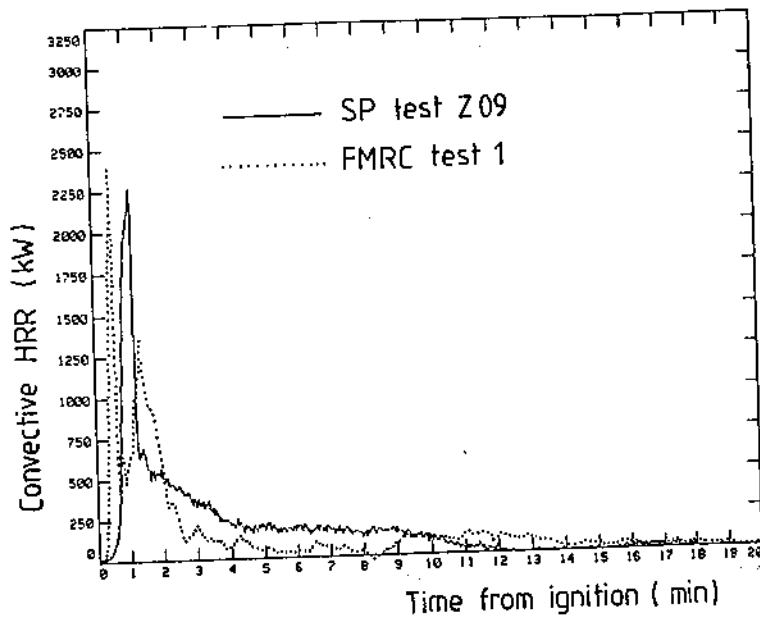


Figure 11. The convective HRR achieved during an ESFR RDD protocol test using the FMRC standard plastic commodity. For comparison purposes, one similar FMRC test [14] is included as a dotted line.

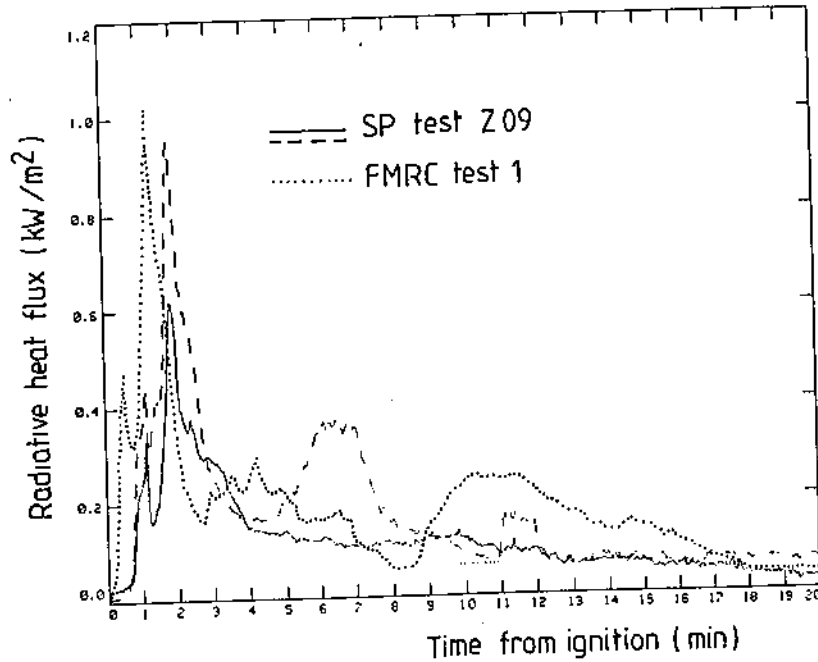


Figure 12. The radiative heat flux achieved during an ESFR RDD protocol test using the FMRC standard plastic commodity. For comparison purposes, one similar FMRC test [14] is included as a dotted line.

7.1.2 3-Tier high FMRC standard plastic commodity

Three 3-tier high tests conducted at SP and five similar tests conducted at FMRC were used as comparisons [12]. Test conditions and results are shown in table 3.

Table 3. 3-tier high tests using the FMRC standard plastic commodity conducted at FMRC [12] and SP respectively to study the reproducibility of the RDD-test method.

Test org/ test No	FMRC #93	FMRC #98	FMRC #92	FMRC #86	FMRC #102	SP Z07	SP Z05	SP Z06
Water density (mm/min)	11.8	13.9	13.9	17.5	18.7	14	17.5	20
HRR at water appl (kW)	1800	1900	1900	1900	1900	1955	1915	1770
Conv heat released (MJ)	*	*	*	*	*	335	218	147
Suppressed	No	No	Yes	Yes	Yes	No	Yes	Yes

* No results were reported in the extract of report received from FMRC.

The HRR-curves in figure 13 show that the results from the tests at FMRC and SP are very similar. The tests at 18.7 mm/min and 20 mm/min respectively results in a definite suppression. Also at 17.5 mm/min, the suppression is definite even if the reduction of HRR are slightly slower. At 13.9 mm/min, FMRC has conducted two tests, one resulting in suppression and one in redevelopment of the fire. The test at SP at 14 mm/min resulted in a redevelopment of the fire very similar to one of the tests at FMRC. As shown in table 3, the integrated HRR decreased proportionally with increasing water density in the SP tests.

Also in these tests, the radiation measurements are influenced by the location of the flames. The maximum value was however approximately 0.5 kW/m² at 6.25 m in both tests resulting in suppression.

Both test series at FMRC and SP resp, show that the bracket for a 3-tier high FMRC standard plastic commodity is 14-17.5 mm/min.

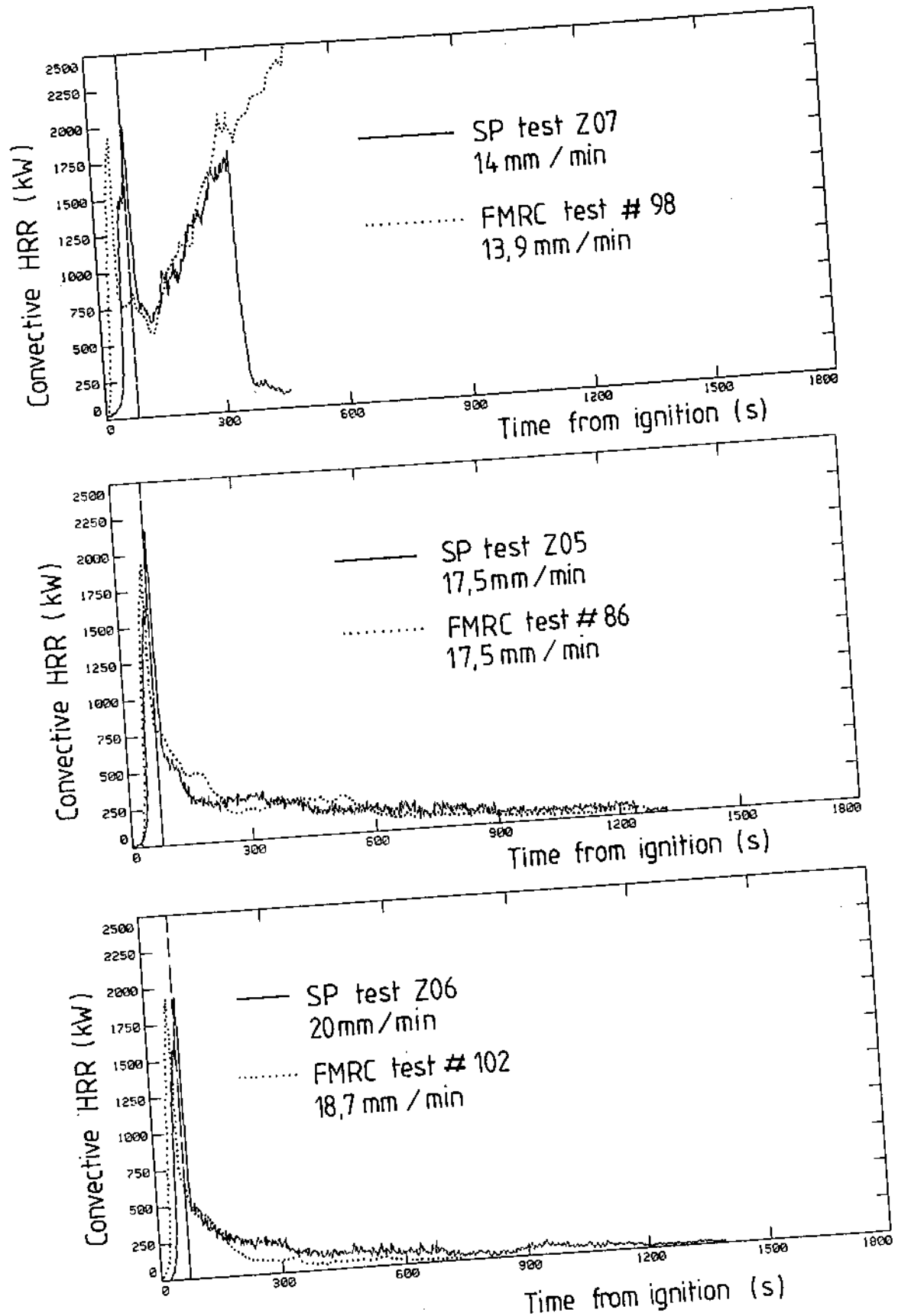


Figure 13. The convective HRR curves obtained for 3-tier high FMRC standard plastic commodity when using various water densities. For comparison purposes, three similar FMRC tests [12] are included as dotted lines.

7.1.3 Swedish CEA-commodities

Furthermore, three tests using a post pallet test set-up with the Swedish CEA-commodities has been performed under similar conditions both at SP and FMRC [15]. The conditions and results are given in table 4.

The agreement between the tests are good but not as perfect as for the FMRC commodity. The HRR value was in general higher at start of water application in the FMRC tests but in spite of this, the measured convective heat release was lower in all three tests. One reason might be that the initial phase of the fire, before water application, was approximately half a minute longer in the tests at SP as can be seen in figure 14 showing the HRR-curves. This might result in a more intensive fire in the bottom tier of the SP tests making it difficult to suppress the fire and at the same time causing extensive fire damage. The reason to this difference in fire development is not clear. The type and location of the ignition sources and the flue spaces between the commodities were identical. However, one difference is that FMRC used a double-row rack and SP a post pallet system. In the SP tests, the flue spaces became partly blocked by the members of the post pallet rack.

The RDD-bracket given by FMRC for this commodity is 27-30 mm/min, which corresponds well with the results achieved in our own tests in spite of the differences mentioned above.

Table 4. 3-tier high tests using the commodity and post pallet storage configuration conducted at FMRC [15] and SP respectively to study the reproducibility of the RDD-test method.

Test org/ test No	FMRC 3	FMRC 4	FMRC 2	SP Z03	SP Z04	SP Z02
Water density (mm/min)	26.7	30.4	34.1	24	30	33
HRR at water appl (kW)	4200	3300	3200	2490	2650	2590
Conv heat released (MJ)	>343	101	96	>432	242	113

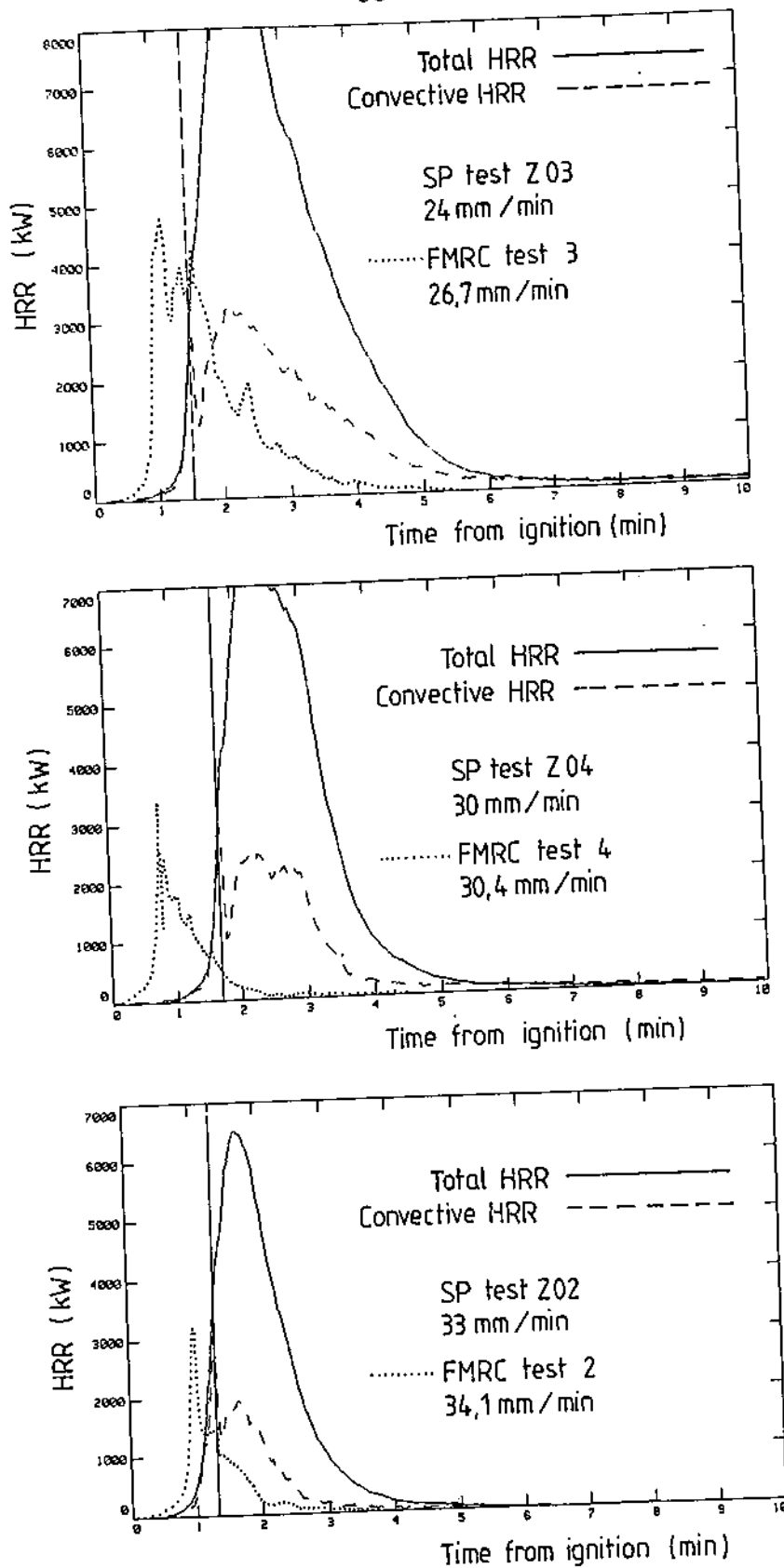


Figure 14. The convective HRR curves obtained for 3-tier high SCEA commodity in a post pallet storage configuration when using various water densities. For comparison purposes, the three similar tests conducted at FMRC [15] are included as dotted lines.

7.2 Comparison of original CEA and Swedish CEA and Large SCEA commodities

RDD-tests have also been conducted with the SCEA-commodity using both 3 and 2 tier high storage for comparison with the original CEA-commodity. Most tests were conducted using a post pallets storage configuration but some were also conducted in a rack storage. Some 2 tier tests have also been conducted with the Large SCEA. The conditions and results from the 3 tier high tests are shown in table 5 and the 2 tier high tests in table 6.

Table 5. Summary of RDD-test conditions and results when using SCEA and original CEA commodities respectively and a 3 tier high storage.

Commodity storage conf. test No	CEA PP (RDD 09)	SCEA PP (RDD 08)	SCEA RS (RDD 10)	SCEA RS (RDD 11)	SCEA PP (Z03)	SCEA PP (Z04)	SCEA PP (Z02)
Water density (mm/min)	33	33	35	27.5	24	30	33
HRR at water appl (kW)	1605	1690	1500	1455	2490	2650	2590
Conv heat released (MJ)	50	85	57	76	>432	242	113

PP=Post pallets RS= Rack storage

Test RDD 08 and 09 are the only two tests which are directly comparable. Studying the HRR-curves in figure 15 and total released heat, there is a tendency that the SCEA commodity has a slightly faster fire development, reaching higher HRR-value before getting suppressed. Also the convective released heat is greater for the SCEA commodity which corresponds with visual damage, 41 % for SCEA and 31 % for CEA commodity. The water density is however above the RDD-bracket for this commodity/storage configuration which makes any differences less noticeable.

The tests Z 02-04 and the similar tests performed at FMRC establish the RDD-bracket for the SCEA commodity to approximately 27-30 mm/min. The single test with the CEA commodity is not enough to establish any RDD-bracket. However, based on the noticed differences also including the 2 tier high tests summarized below, the RDD-bracket for the CEA commodity is probably slightly below the SCEA commodity.

The tests conducted in rack storage (RDD 10-11) show a faster initial fire development, see figure 16. The reason for this is the more narrow flue spaces, 100 mm and 200 mm instead of 270 mm and 355 mm for the SCEA post pallet set-up. The SCEA rack storage seemed also a little bit easier to suppress and even the test using 27.5 mm/min was quite convincing. One possible reason is that the fire gets a faster vertical spreading, preferably in the central flue space, resulting in relatively less fire damage in the bottom tier, making the fire easier to suppress.

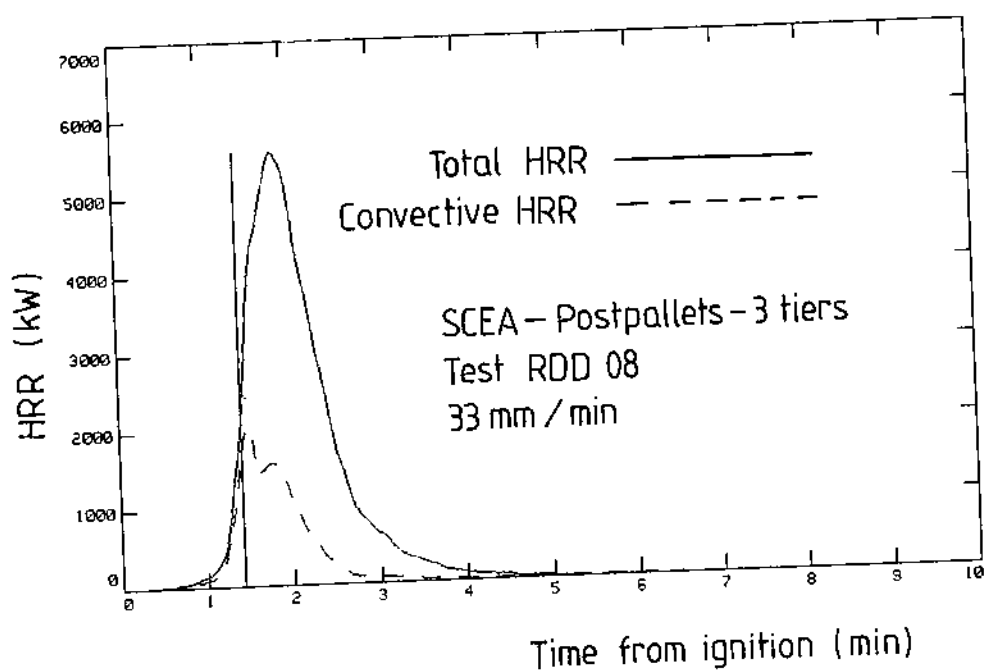
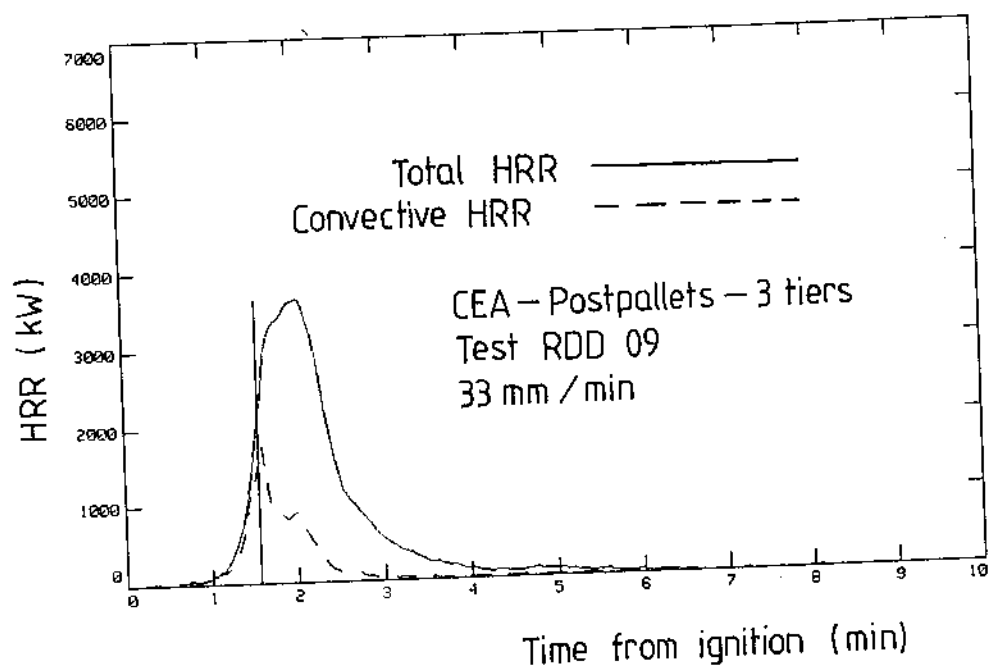


Figure 15. HRR-curves from two similar tests using the original CEA commodity (top) and the SCEA commodity (bottom) in a 3 tier high post pallet configuration. Both tests are conducted using a water density of 33 mm/min.

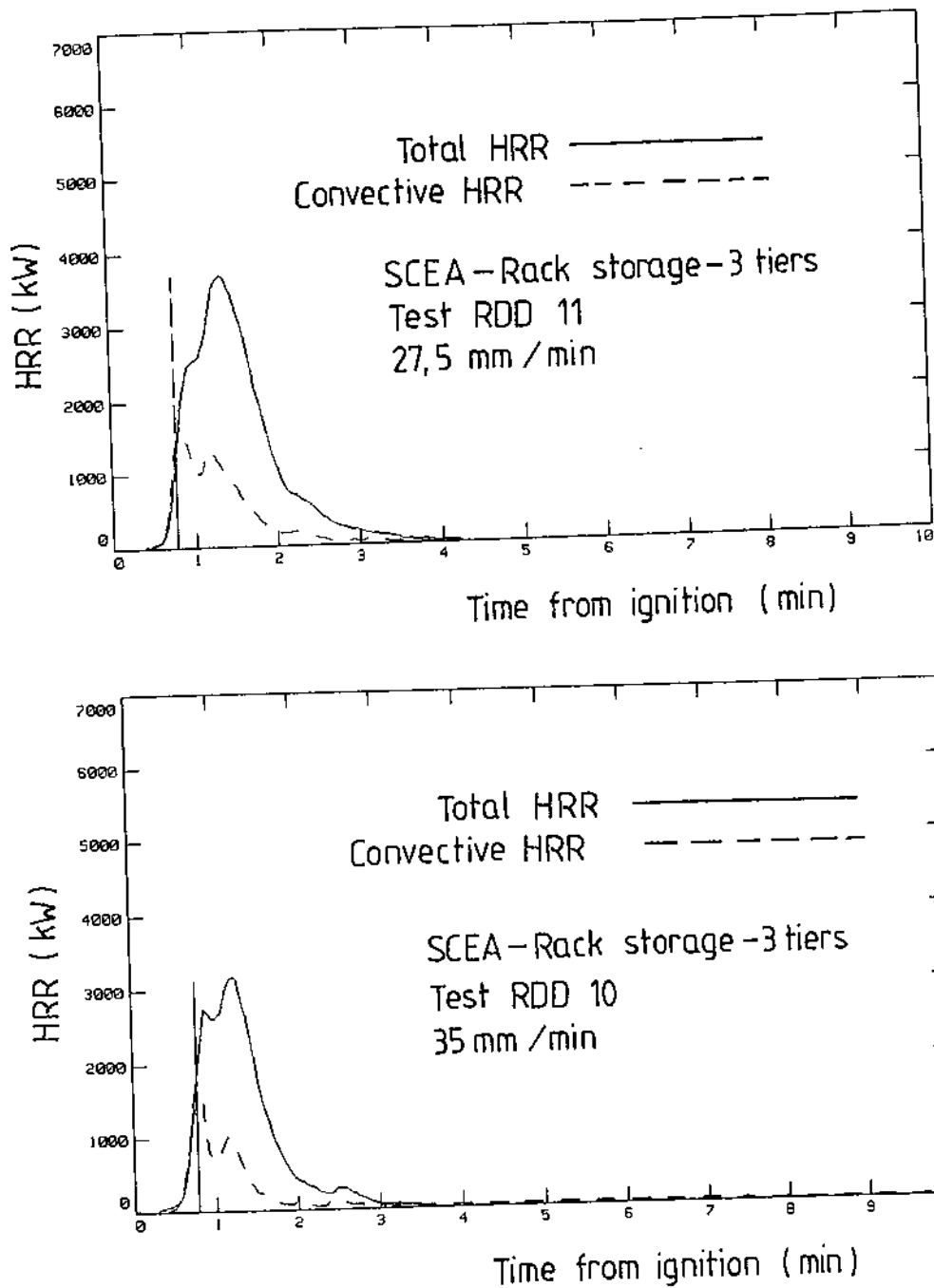


Figure 16. HRR-curves from two similar tests using the SCEA commodity in a 3 tier high rack storage configuration, using a water density of 27.5 mm/min and 35 mm/min respectively.

Also in the tests with 2 tier high storage, fire growth rate is greater for the SCEA commodity and the maximum HRR (both total and convective) after water application is higher. At the same water density, this results both in more released convective heat and visual damage for the SCEA commodity, see table 6.

Enough tests have not been conducted to establish any definite RDD-brackets for these 2 tier high post pallet configurations. The tests with the original CEA commodity show, however, that a water density of 13 mm/min probably is just above the lower limit of a RDD-bracket, see figure 17.

The SCEA commodity achieved approximately the same visual fire damage and release approximately the same amount of convective heat when using a water density of 18 mm/min as the CEA commodity when using 13 mm/min. Based on this tendency, the RDD-bracket for the 2 tier high SCEA commodity seems to be around 16-18 mm/min, see figure 18.

The tests with the Large SCEA show that this seems to be comparable or even slightly more difficult to suppress than the SCEA commodity, see figure 19.

Table 6. Comparison of conditions and results when testing original CEA, SCEA and Large SCEA commodities in a 2 tier high post pallet storage configuration.

Commodity / test no	CEA (RDD 13)	CEA (RDD 14)	CEA (RDD 07)	SCEA (RDD 06)	SCEA (RDD602)	Large SCEA (RDD01)	Large SCEA (RDD02)	Large SCEA (RDD03)
Water density (mm/min)	13	15	18	18	18	13	13	22.5
HRR at water appl (kW)	1540	1690	1460	1420	2590	2510	1675	1265
Conv heat released (MJ)	131	107	79	133	176	342 *	214 *	46

* Manually terminated

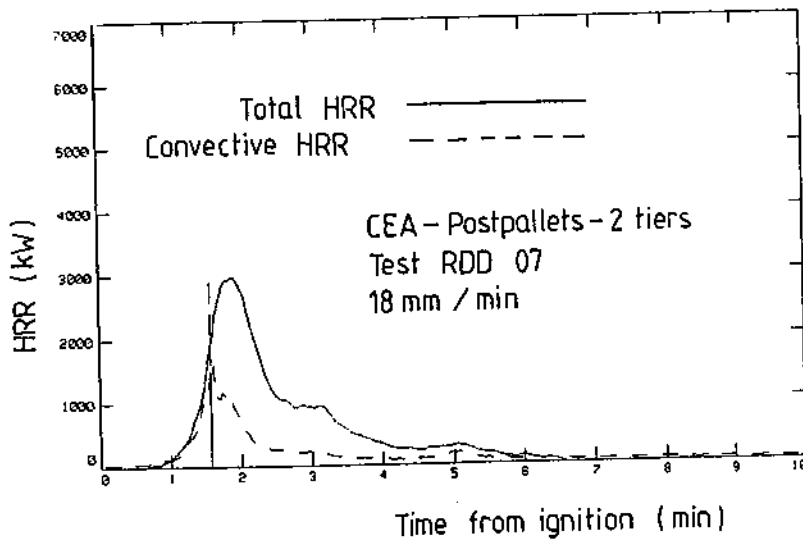
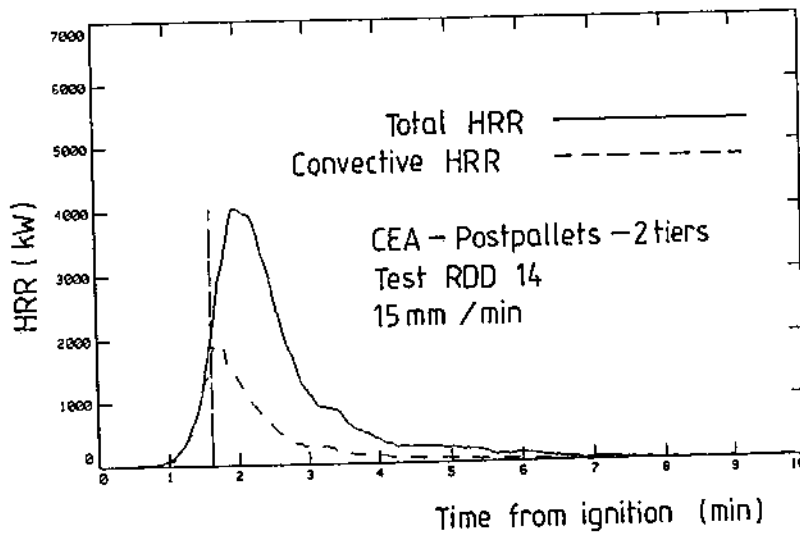
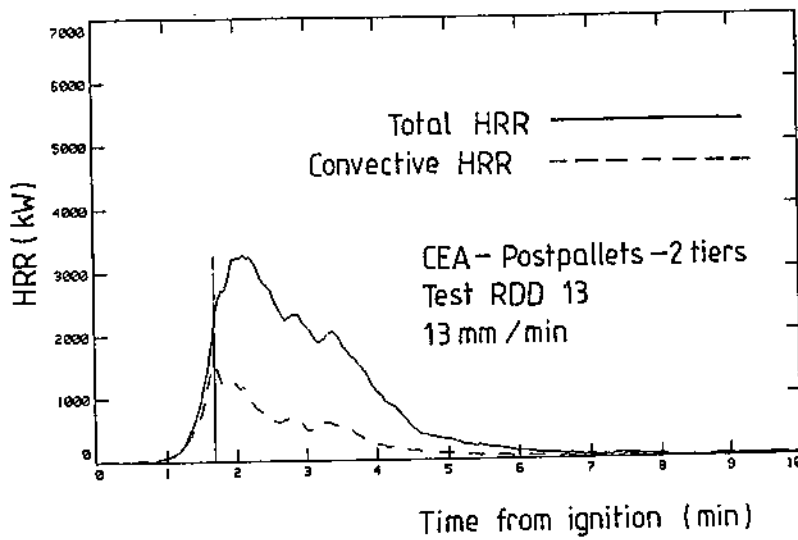


Figure 17. The convective HRR curves obtained for 2 tier high original CEA commodity in a post pallet storage configuration when using various water densities.

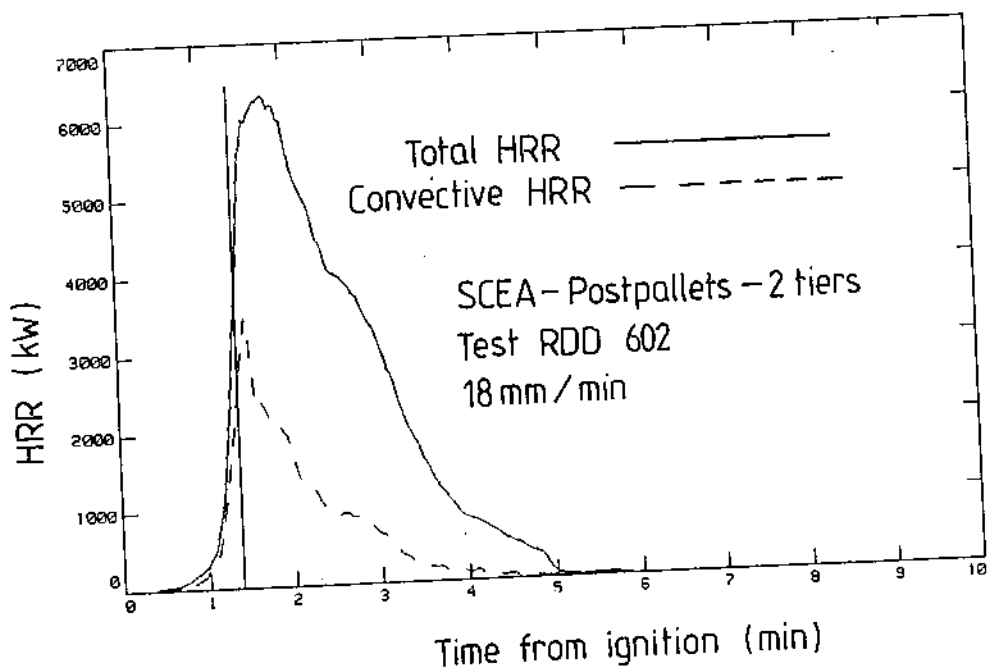
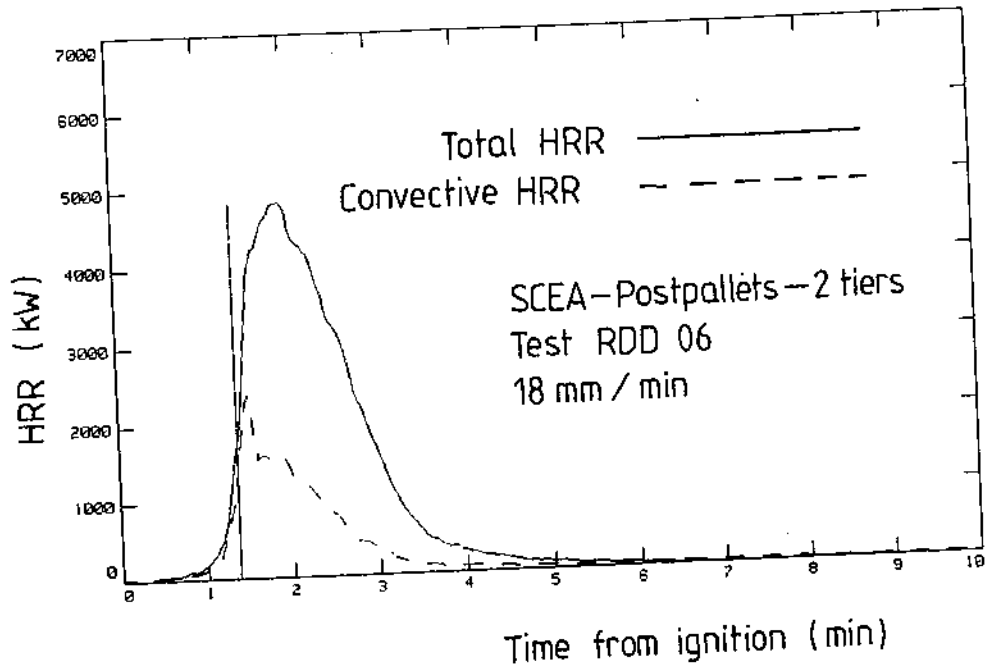


Figure 18. The convective HRR curves obtained for 2 tier high SCEA commodity in a post pallet storage configuration, using the same water densities but different HRR at start of water application.

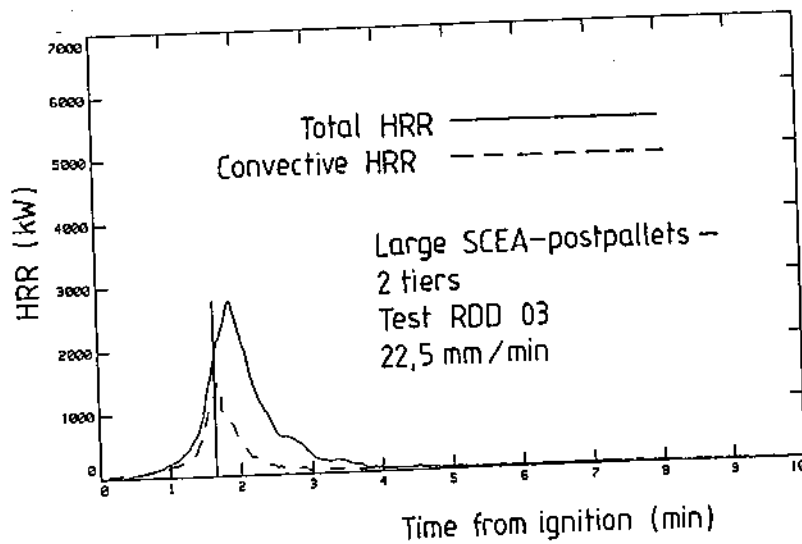
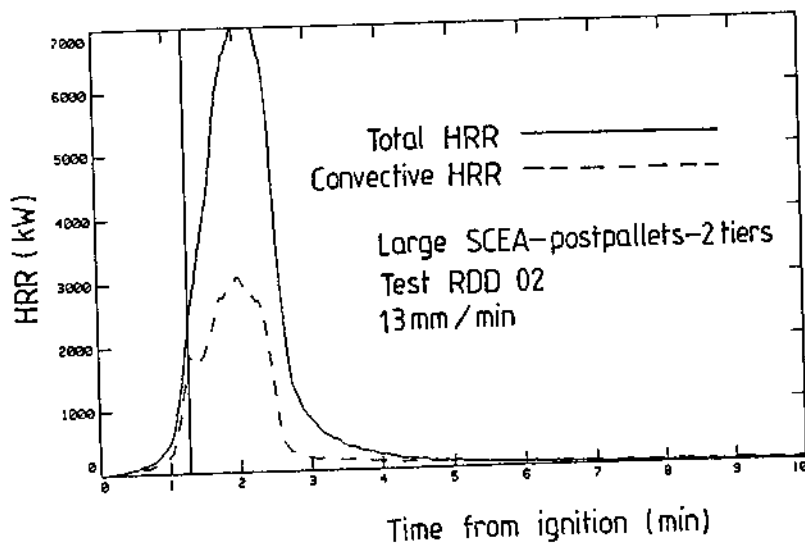
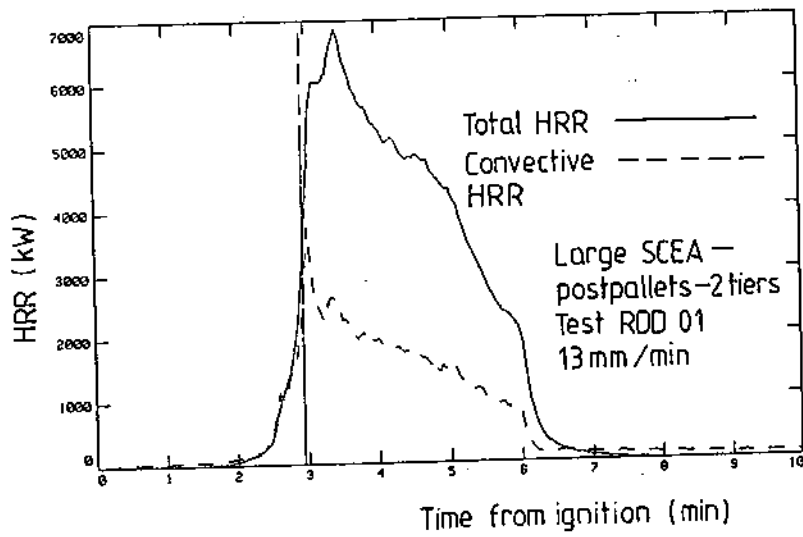


Figure 19. The convective HRR curves obtained for 2 tier high Large SCEA in a post pallet storage configuration when using various water densities.

7.3 General comparison of the FMRC, CEA and SCEA commodities

The fire growth rate seems to be reasonably similar for the FMRC and CEA commodities, while the SCEA commodity seems to be slightly faster as shown in figure 20. The initial phase of the fire is approximately 0:30 second longer for the CEA and SCEA commodities which probably is a result of the larger flue spaces compared to the FMRC storage configuration.

The increased fire growth rate for the SCEA commodity might be a result of the different quality of carton and polystyrene chips. As shown in table 9, the weight of the CEA carton is approximately 15 % higher and the weight of the chips approximately 20 % less compared to the SCEA commodity. This might result in faster fire penetration through the corrugated paper and a larger quantity of exposed chips for the SCEA commodity.

Another difference in fire behaviour between the FMRC and chips commodities is that the HRR stabilizes for a short while on a certain value. In the 3 tier high tests, this value was approximately 1500 kW, and in the 4 tier high storage approximately 2000 kW. The reason is probably that during the first phase, it is mostly the corrugated carton burning and during the steady phase, the polystyrene cups ignite and then contribute to the fire.

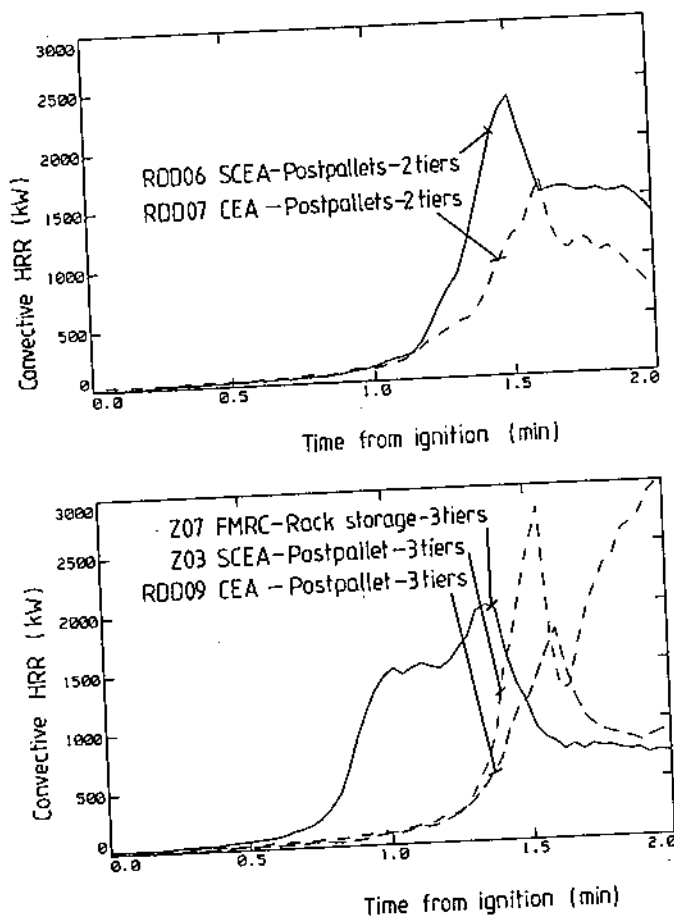


Figure 20. The first initial phase of the HRR histories for the tested commodities. The first diagram shows CEA and SCEA commodities in a 2 tier high post pallet configuration. The second diagram shows FMRC, CEA and SCEA commodities in a 3 tier high rack storage and post pallet configuration respectively.

7.4 Comparison between RDD- and full-scale sprinkler test

7.4.1 Tests conducted at SP-Fire Technology

In connection with various full-scale sprinkler tests performed at SP, some RDD-tests were also conducted to give a possibility for comparison between achieved RDD-results and sprinkler test results. An important question raised by many people is, whether the RDD-test procedure gives results comparable with "real life".

The main purpose with the full-scale sprinkler tests have been to investigate, at the request of various customers, if eg ESFR-sprinklers could be used in their storage facilities or if in-rack sprinklers are necessary, as the type of commodities were judged to be more severe than the type of commodities allowed in the ESFR installation guide lines. The tests have been performed using full pressure from the sprinkler pump to simulate a real situation where the pressure is relatively high, when only a few number of sprinklers have operated, in these tests approximately 8 bar. This means of course a higher flow rate and water density compared to that achieved at the lowest acceptable pressure for ESFR-sprinklers, 3.45 bar.

In all tests the sprinkler spacing has been 3 m x 3 m. The distance between the heat sensing element and the ceiling has been different but within the limits specified in the ESFR installation guide lines, 100-330 mm.

Neither the number of full-scale tests, nor the number of RDD-tests are enough for a very detailed or definite comparison, but they can be used as an attempt to see that the tendency is correct. One difficulty in this comparison, is that the ADD-value for the sprinkler under these tested conditions has to be known. In these cases an approximately ADD-value has been achieved from DMRC for the tests where ESFR-sprinklers have been used. In tests where other sprinklers have been used, information about the ADD-values is lacking making the comparison more uncertain.

The test conditions and the results from the RDD and full-scale tests are shown in table 7 and 8, respectively. Convective HRR curves from the RDD-tests are shown in figure 21.

Table 7. The table summarizes the test conditions and results from RDD-tests using "real" commodities.

	Large SCEA	Furniture	Spare parts	
Storage conf. test No	Rack storage (RDD 15)	Rack storage (Z 08)	Rack storage RV40	RV60
Water density (mm/min)	40	48	40-60	60
HRR at water appl (kW)	1665	2745	1005	1285
Conv heat released (MJ)	>225 *	136	96 *	110

* Manually terminated

Table 8. Summary of full-scale sprinkler tests using the same commodities and storage configurations as used in RDD-tests.

	Large SCEA	Large SCEA	Large SCEA	Fur- niture	Fur- niture	Fur- niture	Fur- niture	Fur- niture	Spare parts
Type of sprinkler	ESFR	ESFR	Konv MR	ESFR	ESFR	Large drop	Large drop	Konv MR	ESFR
K-factor (l/min, kPa ⁻²)	20.6	20.6	8.0	20.6	20.6	16.0	16.0	8.0	20.6
No of sprinklers operating	4	3	15	5	4	5	4	6	3
Flow rate per sprinkler (l/min)	550	570	173	535	560	435	445	225	570
Visual damage (%)**	13	13	>80 *	6	12	14	11 *	50 *	3
Suppressed	Yes	Yes	No	Yes	Yes ***	Yes	No ***	No	Yes

* Damage after manual extinction

** The damage is estimated with the whole test set-up as reference, 32-40 pallets.

*** The goods were irregularly placed in the rack, eg some pallets were put close together along the central flue space.

The full-scale tests with Large SCEA resulted in a very convincing suppression in the two tests using the ESFR sprinklers, while a similar test with normal conventional sprinklers resulted in complete failure. The ADD value for the ESFR sprinklers has been estimated roughly to 42-48 mm/min under these conditions by FMRC. Under non-fire conditions (or after initial knock down of the fire) the design water density based on flow rate and spacing was approximately 60 mm/min. The ADD-value for the conventional sprinkler is not known but the RDD-test conducted using a water density of 40 mm/min did not suppress the fire which seems logical considering the full-scale tests.

Also the tests with the furniture commodity were successfully suppressed in two tests using ESFR-sprinklers, giving approximately the same water densities as in previous tests with Large SCEA. Of the two tests using Large Drop sprinklers, one was successful but in the test with irregular goods the test had to be terminated manually as the fire started to redevelop after the first initial knock down. The fire might have been controlled in the long run but it cannot be considered as a suppression. The ADD-value for the Large Drop sprinklers is not known but the design water density under non-fire conditions was approximately 48 mm/min. One test with conventional sprinklers resulted in failure and this had probably not even been controlled in the long run. The design water density under non-fire conditions was approximately 25 mm/min. The RDD-test conducted using a water density of 48 mm/min suppressed the fire and considering the released convective heat during the test, and the results of the full-scale tests, it may be possible that the RDD-value for the commodity is even slightly lower.

The single full-scale test on spare parts using ESFR-sprinklers also resulted in suppression. The water density conditions were approximately the same as in the Large SCEA and furniture tests. Two RDD-tests were also conducted. The first RDD-test was, based on visual observations during the test, was not considered controlled and the decision was taken to increase the density from 40 mm/min to 60 mm/min during the test. The test was then manually terminated after approximately 2:00 min. The second RDD-test was conducted using a density of 60 mm/min during the entire test. Afterwards, considering the convective HRR and the total released convective heat, the first test should have been conducted without changing the density to really verify whether this had resulted in a failure or not. Based on the released convective heat when using 60 mm/min, there seems to be some marginal to the RDD-value for this commodity. This is also verified by the full-scale test result.

A general conclusion from the RDD-tests is also that the development of a fire in "real goods" might be as fast as for test goods such as polystyrene chips and plastics. Depending on the type of package material, it is mostly the initial phase until the fire starts to increase that differs, see figure 21 and 22. This is very clearly shown in figure 22, where in the first test the time to water application was approximately 11:00 min and in the second test 4:30 min. The reason for this difference was a narrow slit between two pallet rims in the second test, making it possible for the fire to spread into the pallet much faster.

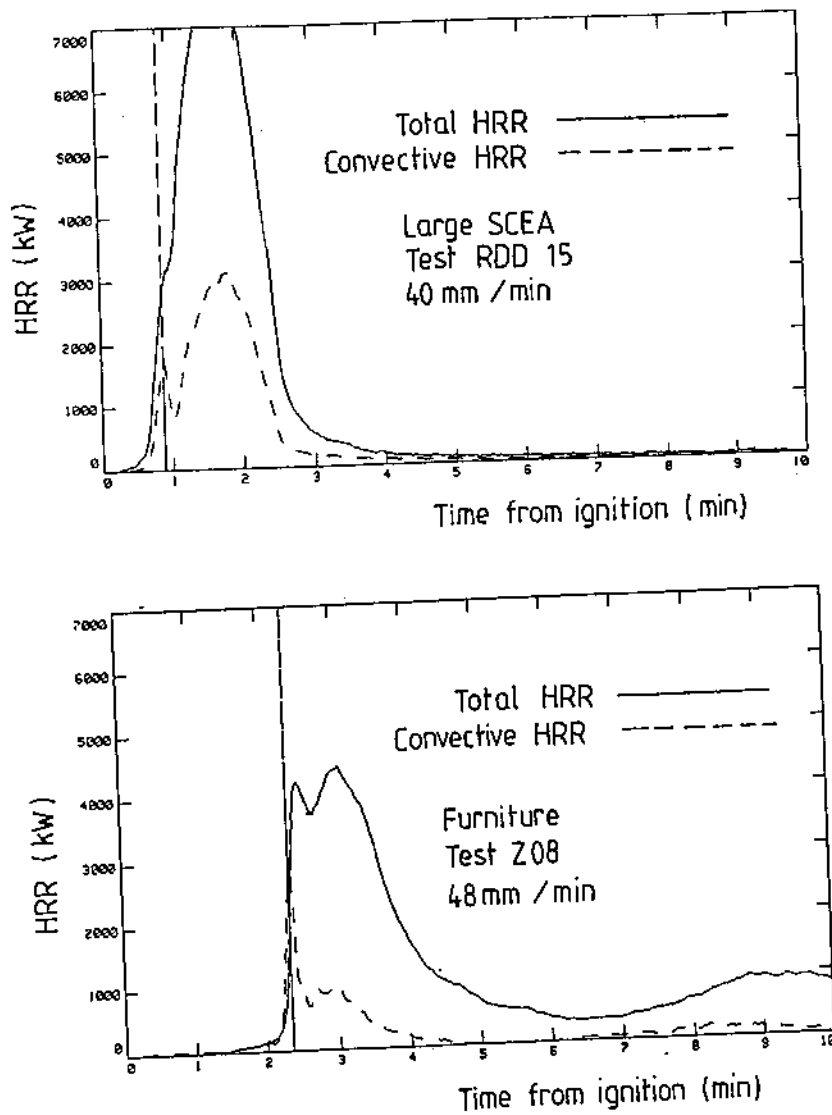


Figure 21. HRR-curves obtained when testing the Large SCEA and furniture commodities using the same configurations as used in full-scale sprinkler tests.

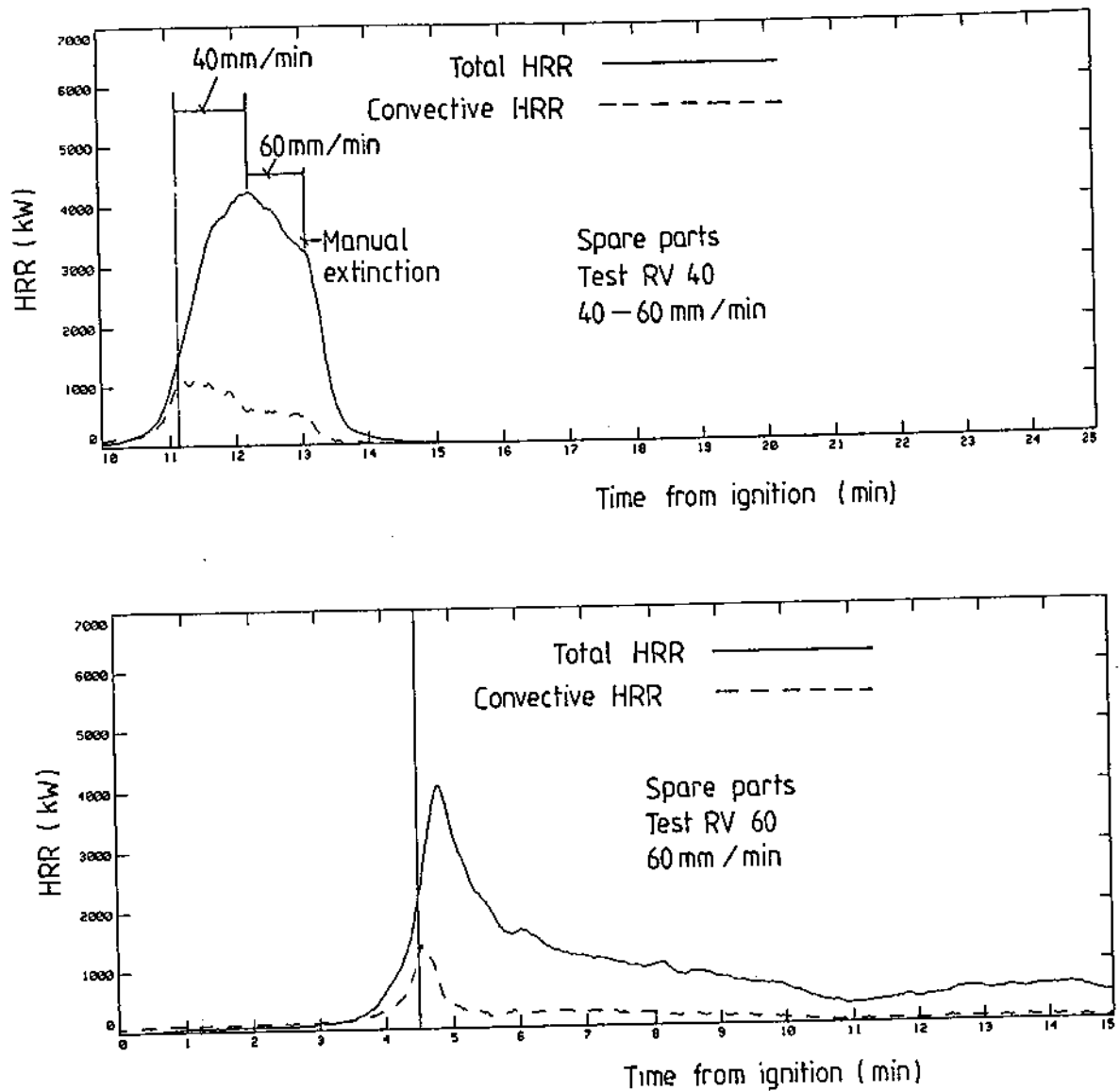


Figure 22 HRR-curves obtained when testing the spare parts commodities using the same configurations as used in full-scale sprinkler tests. During the first test the water density was changed from 40 to 60 mm/min before the test was terminated manually after approximately 2:00 min.

7.4.2 Tests conducted at LPC within the CEA sprinkler research projects

CEA has during several years been sponsoring full-scale sprinkler tests for research purposes. The tests have been conducted at LPC in UK in the Cardington hangar. Most of the results are not reported officially but for comparison purposes we have received the necessary information from these tests [18, 19, 20] to be able to evaluate our RDD-tests conducted with their CEA test commodities. The full-scale tests are conducted below a suspended ceiling, approximately 30 m x 30 m, with a height of 9 m. A lot of parameters have been evaluated, such as storage height, clearance, type of sprinkler, RTI-value, water density, etc. Most tests have been conducted using the post pallet test set-up and a wet system, in this report referred to as CEA commodity but some tests have also been conducted using solid piled storage and a dry system respectively. In most tests the water density has been kept constant during the entire test.

Studying video tapes from some of the tests, we have been able to get an idea of the fire development in the tests. They seem very similar to the development achieved during our RDD-measurements. By studying the time from the point when the flames reach the upper level of the commodities until the sprinkler releases, we have been able to use a realistic HRR-value when to start the water application during the RDD-tests. In our RDD-tests this time delay has been approximately 15-30 sec which is quite similar to the delay measured from the full-scale tests except for tests with very high or low clearance and RTI-values resp.

A very brief summary of the full-scale test results show that a 2 tier storage (3 m) can be suppressed with only a limited number of sprinklers operating at a design water density of 17.5 mm/min when using medium or fast response sprinklers and a clearance of 2-4 m. When clearance was increased to 6 m the design water density had to be increased to 30 mm/min to suppress the fire.

Tests with a 3 tier high storage (4.4 m) and a design water density 17.5 mm/min, were conducted using a clearance of both 2 m and 4.6. Also here, a certain improvement could be noticed with lower clearance, even if a lot of sprinklers operated in both cases. When using 2 m clearance in one test, 18 sprinklers operated resulting in approximately 50 % damage, which might be judged as "control". Using 4.6 m clearance resulted in approximately 30 sprinklers operating and 100 % damage which must be considered as a failure.

Two tests conducted on a 4 tier high storage (approximately 6 m) using a design water density of 40 mm/min, one with a type of large drop sprinkler and one test with an ESFR sprinkler showed very clearly the importance of the sprinkler spray characteristic and the ADD-value. The large drop sprinkler failed to suppress the fire and 26 out of 30 sprinklers operated. When using the ESFR sprinkler, 5 operated with only a limited damage as a result.

Considering the aspect that reported water densities in these tests are design densities and that the ADD values might be more or less below these values, there seems to be a very good correlation with our RDD-tests. The bracket for the 2 tier high commodity is estimated to approximately 13 mm/min, and for the 3 tier high commodity to approximately 27 mm/min. No test has been conducted on a 4 tier CEA commodity. Only one RDD-test using the SCEA commodity and 22.4 mm/min has been conducted by FMRC (ESFR RDD protocol test) which was not suppressed. A similar test using the Large SCEA and a water density of 40 mm/min has also been conducted at SP, also resulting in no suppression.

Considering that the 2 tier Large SCEA seemed to have a higher RDD-value than the SCEA commodity, which in turn seems to have a higher RDD-value than the CEA commodity, the outcome of the two full-scale tests seems logical. The RDD-value for the commodity might be just below 40 mm/min which seemed to be low enough for the ESFR sprinkler but too high for the large drop sprinkler which probably has an ADD-value below the RDD-value.

7.5 Results of freeburn tests

In order to quantify the fire load and possible heat release from a pallet load, a single pallet of the various test commodities has been tested also free burning under the FPC equipment and HRR curves are shown in figure 23. Based on this kind of test it is possible to quantify the fire damage during a RDD-test in an objective way. The total heat release during the RDD-test is put into relation to the possible heat release obtained in a free burn test making it possible to calculate the damage (amount of burned material).

The results from the free burning tests are summarized in table 9. The results show clearly the great difference between the FMRC commodity and the "chips commodities". The weight of the FMRC pallet load is approximately 3-4 times more and has a heat of combustion which is 4-5 times more compared to the "chips commodities". From this point of view, the FMRC commodity seems to represent "real" commodities more closely.

Table 9. The table summarizes the properties of the used test commodities and the results of free burn tests of one pallet load using the FPC equipment.

Commodity	FMRC	CEA	SCEA	Large SCEA
Weight poly-styrene/carton (g)	4125	340	420	1220
Weight carton (g)	2725	805	700	1470
Weight pallet (kg)	24	9.6	9.6	9.6
Total weight of one pallet load (kg)	78.8	23.4	23.1	20.4
Heat of comb. carton (MJ/kg)	18.0 [11]	14.9	16.3	16.3
Heat of comb. pallets (MJ/kg)	18.0 [11]	17.0 *	17.0 *	17.0 *
Heat of comb. poly-styrene (MJ/kg)	39.0 [11]	39.6	38.0	38.0
Theoretical heat of combustion (MJ)	2111	469	492	444
Conv heat released (MJ)	2311 [11]	260	203	137
Total heat released (MJ)	993	321	291	222
Measured heat of combustion of one pallet load (MJ/kg)	1658	13.7	12.6	10.9

* Estimated value

A comparison of the CEA and SCEA commodities show that the weight of the total pallet load is almost the same but the relation in weight of the carton and chips differs. The CEA commodity has higher weight of the carton while the weight of chips is less compared to the SCEA commodity. This might be the reason for the slightly different behaviour in the RDD-tests.

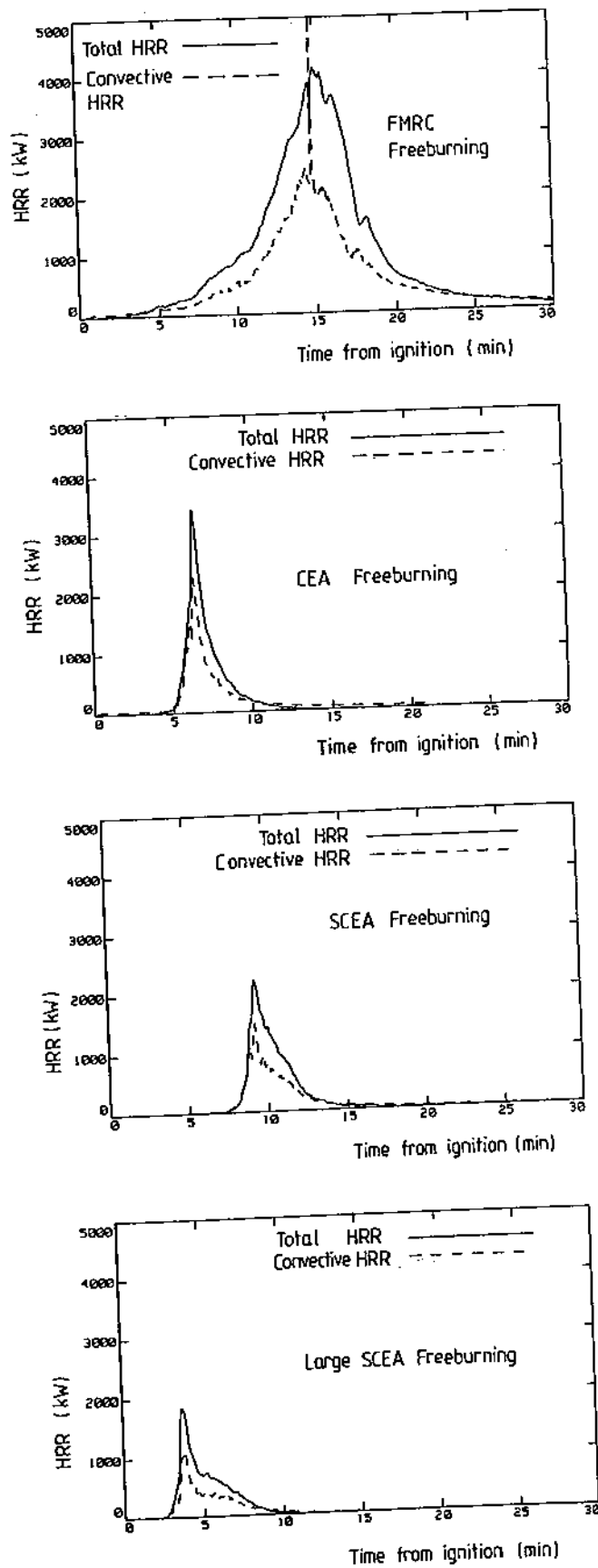


Figure 23. HRR histories achieved during free burning tests with one single pallet load of the tested commodities, FMRC, CEA, SCEA and Large SCEA.

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Annex A

Table A1. Summary of test conditions and results obtained in the first part of the test series including original CEA, SCEA and Large SCEA commodities.

Test No	Comin/ storage conf.	Tiers	Water density (mm/ min)	Flames above goods (min.s)	Start water appl. (min.s)	Time delay *** (min.s)	HRR konv at start (kW)	Visual damage (%)	Visual damage Tier 1 (%)	Visual damage Tier 2 (%)	Visual damage Tier 3 (%)	Visual damage Tier 4 (%)	HRR konv max (kW)	HR konv total (MJ)	Radia- tion max (kW/ m ²)	Radia- tion total (kJ/m ²)	Inte- gration time (min.s)
RDD01	Large SCEA postp	2	13	2.25	2.56	0.31	2510	81 **	NM	NM	-	-	3750	342.2	NM	NM	5.04
RDD02	Large SCEA postp	2	13	0.58	1.16	0.18	1675	NM **	NM	NM	-	-	3080	214.3	NM	NM	4.34
RDD03	SCEA postp	2	22.5	1.20	1.39	0.19	1265	45	58	31	-	-	1475	46.3	NM	NM	6.51
RDD06	SCEA postp	2	18	1.05	1.22	0.17	1420	57	66	48	-	-	2365	133.3	NM	NM	7.18
RDD 602	SCEA postp	2	18	0.59	1.23	0.24	2590	65	74	56	-	-	3470	176.3	NM	NM	4.31
RDD07	CEA postp	2	18	1.05	1.34	0.29	1460	40	43	36	-	-	1660	79.2	NM	NM	7.26
RDD08	SCEA postp	3	33	1.09	1.25	0.16	1690	41	45	64	13	-	2030	84.6	NM	NM	7.10
RDD09	CEA postp	3	33	1.14	1.34	0.20	1605	31	40	40	14	-	1780	50.4	NM	NM	6.56
RDD10	SCEA rack storage	3	35	0.33	0.47	0.14	1500	25	33	35	7	-	1585	57.1	NM	NM	8.13
RDD11	SCEA rack storage	3	27.5	0.34	0.46	0.12	1455	33	39	48	11	-	1545	75.9	NM	NM	7.44
RDD13	CEA postp	2	13	1.12	1.41	0.29	1540	63	62	65	-	-	1540	130.5	NM	NM	11.49
RDD14	CEA postp	2	15 *	1.03	1.37	0.34	1690	55	49	60	-	-	1885	107.0	NM	NM	8.24
RDD15	Large SCEA rack storage	4	40	0.37	0.53	0.16	1665	70 **	70	100	89	22	3120	224.8	NM	NM	4.07

* Not verified by calibration of the water applicator

** The test was terminated manually

*** Indicates the time delay between the time when the flames reached the top of the fuel array and start of water application. This figure made it possible to better compare the results with tests conducted within the CEA-project.

NM Not measured

Table A2. Summary of test conditions and results obtained in the second part of the test series including FMRC, SCEA and "real" commodities.

st o	Comm/ storage conf.	Tiers	Water density (mm/ min)	Flames above goods (min.s)	Start water appl. (min.s)	Time delay *** (min.s)	HRR konv at start (kW)	Visual damage (%)	Visual damage Tier 1 (%)	Visual damage Tier 2 (%)	Visual damage Tier 3 (%)	Visual damage Tier 4 (%)	HRR konv max (kW)	HR konv total (MJ)	Radia- tion max (kW/ m ²)	Radia- tion total (kJ/m ²)	Inte- gra- tion time (min.s)
12	SCEA	3	33	ca 1.00	1.20	ca 0.20	2590	46	65	66	7	-	2735	113,4	1.60	80	6.40
13	postp SCEA	3	24	ca 1.20	1.31	ca 0.11	2490	75	96	96	32	-	3285	432,4	3.06	263	12.00
14	postp SCEA	3	30	ca 1.30	1.41	ca 0.11	2650	63	81	88	19	-	2940	242,0	1.50	186	7.34
15	postp FMRC rack	3	17.5	ca 0.40	1.17	ca 0.37	1915	31	34	33	6	-	2160	218,4	2.08	143	19.18
16	storage FMRC rack	3	20	ca 0.35	1.12	ca 1.07	1770	30	33	53	3	-	1935	147,4	0.54	261	19.26
17	storage FMRC rack	3	14	NM	1.19	-	1955	33 **	37	52	10	-	2005	335,3	0.59	92	5.41
19	storage FMRC rack	4	22.4	NM	1.07	-	2150	29	45	60	9	3	2270	155,5	0.62	133	19.18
18	storage Furniture	4.5	48 *	NM	2.20	-	2745	NM	NM	NM	NM	NM	3020	135,6	0.70	98	19.43
V40	Spare parts	5	40-60 *	NM	11.07	-	1005	NM **	NM	NM	NM	NM	1150	96,4	0.56	58	3.27
V60	Spare parts	5	60 *	NM	4.30	-	1285	NM	NM	NM	NM	NM	1415	110,0	NM	NM	11.48

Not verified by calibration of the water applicator

* The test was terminated manually

** Indicates the time delay between the time when the flames reached the top of the fuel array and start of water application. This figure made it possible to better compare the results with tests conducted within the CEA-project.

M Not measured

Annex B

B.1 Calibration of water density from the RDD water applicator

In order to verify that the water densities calculated based on flow rate and the coverage area of the water applicator correspond with real water density some calibration tests have been conducted. One major concern was that the applicator was designed to suit rack storage using normal EUR-pallets, 800 x 1200 mm and 100 mm and 200 mm flue spaces along the long and short side of the pallets respectively. Both the FMRC commodity and the CEA and SCEA commodities using post pallets did not correspond perfectly to the positions of the water nozzles on the water applicator, which was considered to possibly influence the real delivered density.

The calibration was conducted by having two steel pans with sizes equal to the various commodity sizes placed below the applicator, using the same flue spaces etc as for the real commodities. Tests were then conducted using various presumed water densities and by measuring the collected volume of water in the pans, the real density was calculated.

The calibration tests conducted are summarized in table B1, and the results show that the applicator gives an accurate water density when normal EUR rack storage is tested. Also the FMRC-commodity achieved correct water density, while the SCEA post pallet commodity received slightly lower densities than presumed. The CEA commodity was not simulated but has been judged to receive the same real density as the SCEA commodity.

The water densities used in this report are the real delivered densities based on these calibration results but rounded up to the nearest half mm/min.

Table B1. The table summarizes the calibration results of the RDD water applicator where various storage configurations have been simulated.

Simulated commodity	Presumed water density (mm/min)	Flow rate (l/min)	Nozzles	Time of measurement (min:s)	Real water density (mm/min)
FMRC	15.2	111	1/8GG5.6W	5:00	15.1
FMRC	17.5	128	1/8GG5.6W	5:00	17.5
FMRC	22.6	164.5	1/8GG5.6W	4:00	22.7
SCEA/PP	14.9	72.5	1/8GG5.6W	5:00	12.8
SCEA/PP	19.8	97	1/8GG5.6W	5:00	17.7
SCEA/PP	24.9	121	1/8GG5.6W	4:00	22.3
SCEA/PP	25.1	122	1/4HH14W	4:00	22.8
SCEA/PP	27.3	132.5	1/4HH14W	4:20	24.2
SCEA/PP	29.9	145.5	1/4HH14W	3:00	28.0
SCEA/PP	35	170	1/4HH14W	3:00	32.9
SCEA/RS	35.8	174	1/4HH14W	3:00	35.6
SCEA/RS	40.3	196	1/4HH14W	3:00	40.9

SP
Swedish National Testing and Research Institute
P.O.Box 857, S-501 15, BORÅS, SWEDEN
Telephone: + 46 33 16 50 00, Telefax: + 46 33 13 55 02

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