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FINAL REPORT

Carl Wilen
Aimo Rautalin

SAFETY-TECHNICAL CHARACTERISTICS OF FOREST RESIDUE, COAL AND STRAW

MASTER

Espoo, May1995
Finland

BIOENERGIAN TUTKIMUSOHJELMA
BIOENERGY RESEARCH PROGRAMME

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FINAL REPORT

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SAFETY-TECHNICAL CHARACTERISTICS OF BIOMASSES
Bioenergia Research Programme - 305
ENE 3137 - KTM 445/881/92

Espoo, May1995
Finland

_Jakelu: Tutkimusohjelman johtoryhmä
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BIOENERGIAN TUTKIMUSOHJELMA

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Biomassojen turvallisuustekniset ominaisuudet (Loppuraportti)

Tiivistelmä

Tutkimuksessa on selvitetty biomassojen itsesyttymiseen ja pölyräjähdyksiin liittyviä turvallisuustekijöitä. Korotetussa alkupaineessa (1-9) bar on selvitetty pölyräjähdyksien tunnuslukuja ja inertisoinnin vaikutusta pölyräjähdysten maksimipaineeseen (pmax.) ja maksimi paineennousunopeuteen (Kstmax.). Erilaisissa alkupaineissa on selvitetty myöskin pölyräjähdysten syntymisen kokonaan estävän inertisointitason suuruutta.

Polttoaineiden itseyttymisherkkyyttä ja paineen vaikutusta itsesyttymisherkkyyteen ja -lämpötilaan on selvitetty paineistettavalla, dynaamisella itsesyttymislaitteistolla. Tutkimuksessa on tarkasteltu inertisoinnin vaikutusta itsesyttymislämpötilan suuruuteen ja mahdollisuuksia itsesyttymisen estämiseen tehokkaalla inertisoinnilla painealueilla 1 ja 25 bar. Sovellutusesimerkkinä on laboratoriokoelaitteessa saatuja tuloksia laskennallisesti eksrapoloitu vastaamaan myöskin käytännössä olevia siilokokoja.

Itseyttymiseen vaikuttavana tekijänä on eri polttoaineilla selvitetty niiden juoksevuutta siiloissa ja lock-hoppereissa (liikkumattomat polttoainekerrokset ovat erityisen alttiita itsesyttymiselle) jatkuvassa ja 1h varastointiajaksi pysähtyneessä virtauksessa. Juoksevuusmittauksissa on käytetty polttoaineen leikkaukseen perustuvia Walkerin pyörivää rengasleikkauslaitetta ja Jeniken lineaarista leikkauslaitetta. Polttoaineen lämpötilan (22 °C, 140 °C) vaikutusta juoksevuuteen on selvitetty metsätähdehakkeen osalta. Polttoaineiden ja käsittelylaitteen välisiä dynaamisia kitkakertoimia on määritetty ruostumattomalle teräkselle ja ruosteiselle teräspinnalle.

Sovellutusesimerkkinä on laboratoriokoelaitteissa saatuja tuloksia laskennallisesti eksrapoloitu tilavuudeltaan 21 m3 siilolle siten, että on laskettu erilaisten hiilien ja metsätähdehakkeen osalta massavirtauksen toteutumiseksi vaadittavan minimipurkausaukon ja kartio-osan minimikaltevuuskulman suuruus siilomateriaalin ollesssa ruostumatonta terästä.

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Carl Wilén, Aimo Rautalin	Safety-technical characteristics of biomasses

Title

Safety-technical characteristics of biomasses (Final report)

Abstract

Safety-technical factors related to spontaneous ignition and dust explosions of biomasses were investigated. Parametres of dust explosions and effect of inertisation on the maximum pressure (pmax) and the maximum rate of pressure rise (Kstmax) were studied at elevated initial pressure (1 - 9 bar). The level of inertisation required to prevent dust explosions totally was determined at different intial pressures.

The sensitivity of fuels to spontaneous ignition and the effect of pressure on the sensitivity to and temperature of spontaneous ignition were studied on a pressurised dynamic self-ignition equipment. The effect of inertisation on the self-ignition temperature and alternatives of preventing spontaneous ignition by effective inertisation in the pressure ranges of 1 and 25 bar were investigated. As an example of application, results obtained with the laboratory test equiment were extrapolated to bin sizes used in practice.

As a factor contributing to spontaneous ignition, the flowability of different fuels in bins and lock-hoppers (stagnant fuel layers are especially sensitive to spontaneous ignition) in continuous flow and in flow stopped for a storage time of 1 hour was also studied. Walker's rotating ring shear equipment and Jenike's linear shear equipment based on shearing the fuel were used in the flowability measurements. The effect of fuel temperature (22 °C, 40 °C) on flowability was determined for forest residue chips. Dynamic friction coefficients between fuels and handling equipment were determined for stainless steel and rusty metal surface.

As an example of application, results obtained with laboratory test equipment were extrapolated to a bin size of 21 m3 by calculating the size of the minimum discharge opening required by mass flow ofdifferent coals and forest residue chips and the minimum angle of repose of the conical part for a bin of stainless steel.

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PREFACE

This report presents the results of the research project "Safety-technical characteristics of forest residue, coal and straw". The overall objectives of the two-year project were:
- to carry out explosion and inerting tests with forest residue dust at elevated pressure and/or temperature to complement the existing safety data by measurements in conditions close to those of PFBG and PFCB plants,
- to perform self-ignition tests with selected biomass fuels and coal at high pressure and especially to study the use of flue gases as inerting agents to prohibit spontaneous ignition,
- to study the flowability of these fuels.

The work programme was completed according to the plans except for the high-pressure and high-temperature dust explosion tests. These experiments have been postponed due to serious dispersion problems of the forest residue dust into the test vessel, and will be reported as soon as completed in a separate report.

The results of the project are reported in the enclosed three separate task reports:

1. Explosion tests with forest residue dust
2. Spontaneous ignition tests
3. Flowability tests

The work was carried out at VTT Energy, Energy production technology, Gasification research group over the years 1993 - 1994. The explosion tests at elevated initial pressure were conducted by Laboratorio Oficial J. M. Madariaga, Madrid, Spain. The flowability tests at elevated temperature were carried out by Jenike & Johanson, inc., USA. The project was funded by:

- the Finnish National Bioenergy Programme (TEKES)
- A. Ahlstrom Corporation
- Enviropower Inc.
- Imatran Voima Oy
- Project Group Elsam/Elkraft
- BCC/Coal Technology Development Division

Espoo, May 1995

Carl Wilén
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VTT ENERGY

SAFETY-TECHNICAL CHARACTERISTICS OF FOREST RESIDUE, COAL AND STRAW

PART 1. EXPLOSION TESTS WITH FOREST RESIDUE DUST

by

CARL WILÉN
AIMO RAUTALIN

CONTENTS

1   GENERAL

Existing information on the assessment of risk and presciption of safety measures is largely concerned with dust explosions initiated at atmospheric pressure and temperature. As the power industry is changing over to processes operating at high pressures and temperatures, the knowledge of safety-technical basic characteristics of fuels is of essential significance when designing handling and feeding equipment, planning safety systems and instructions and evaluating fire and explosion hazards.

In previous studies, complete dust explosion tests have been carried out with peat and forest residue dust at initial pressures of 1 - 4 bar and temperatures of 25 - 200 °C [1]. The tests were carried out by DMT of German on commission of VTT in a 1 m³ vessel. The gasifier of a IGCC process operates on a level of 20 - 25 bar, and hence, much of fuel handling is carried out at even higher pressures.

The aim of this study was to complement the dust explosion study of green wood chips by measurements at 9 - 25 bar initial pressure, as far as possible, Appendix 1. The measurements at the high pressures required cooperation with organizations providing dust explosion tests. Several companies offering services in this field was identified. A survey of the different test possibilities was completed during the spring 1993. It was decided the testing at elevated initial pressure at Laboratorio Oficial J.M. Madariaga in Madrid, Spain. Tests at elevated pressure and temperature was carried out at TNO, The Netherlands.

2   DUST EXPLOSION TESTING

2.1   Explosion severity

The explosion severity is usually expressed in terms of

- maximum explosion overpressure P_{max}
- maximum rate of pressure rise $(dP/dt)_{max}$ and K_{St}
- limiting oxygen content (LOC) in inertial cases.

The explosion index K_{St} is defined as the maximum rate of pressure rise with time $(dP/dt)_{max}$ of an explosion in a closed volume V, according to the so-called cubic relationship (ISO):

$$K_{St} = \left(\frac{dP}{dt}\right)_{max} * V^{1/3}$$

The symbol K_{St} is often reserved for the maximum value of K_{St} determined over a wide range of dust concentrations. Figure 1 shows a schematic drawing of a pressure-time plot during a dust explosion in a closed vessel /2/.
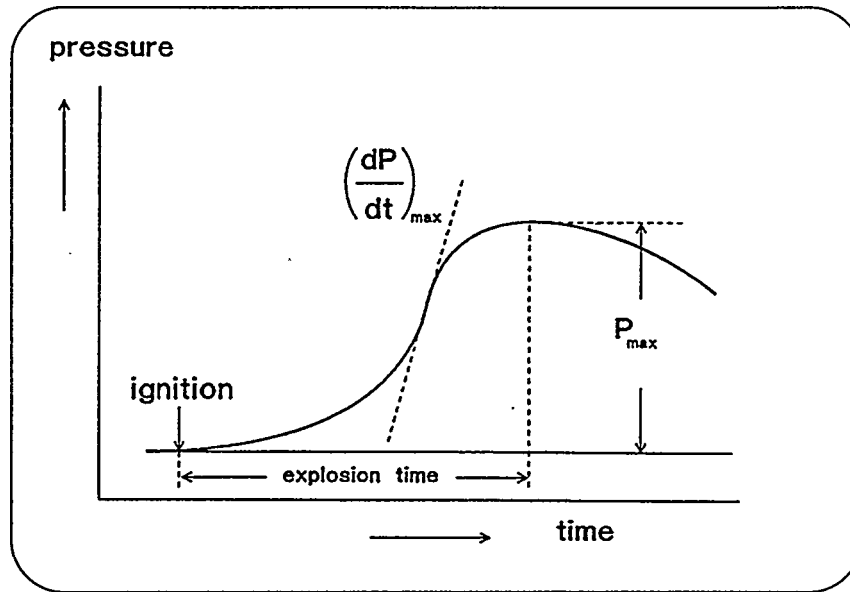
Figure 1. Recording of pressure P against time t, during an explosion [2].

2.2   Dust explosion test equipment

Many types of apparatus have been developed to measure the above mentioned parameters. The 1 m³ vessel is the only really standard piece of equipment [2]. For testing of expensive powders, an explosion vessel with a volume of 20 litre has been developed. This vessel is now in use in many countries, because it is much easier and cheaper to operate than the large

Figure 2. Comparison of explosion data measured in laboratory equipment and the 20 litre sphere with those obtained in the 1 m³ vessel [4].

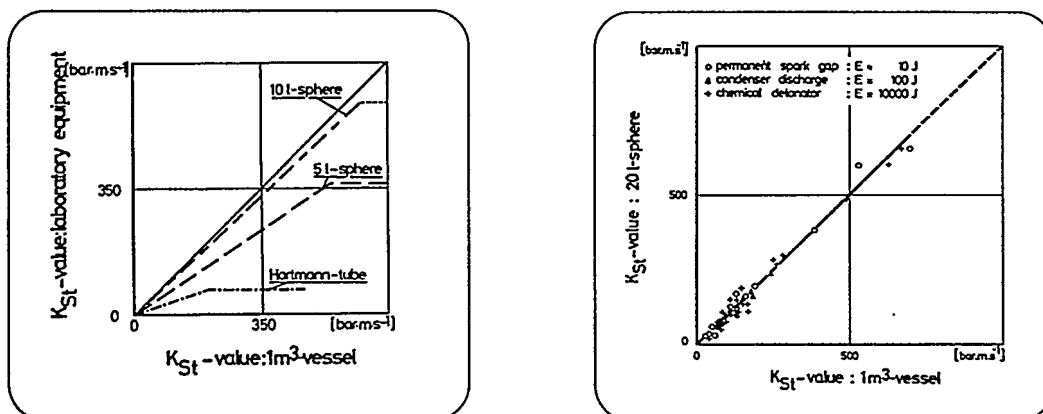standardised vessel, and requires considerably less powder. The conformity in results between small vessels and the 1 m³ vessel has been assessed by Bartknecht [4]. Figure 2 shows a comparison of K_{St}-values measured in different laboratory equipment with those obtained in a large vessel. Bartknecht concluded, that the values for the maximum explosion pressure P_{max} are slightly lower in the small vessel compared with those measured in the large vessel, and that the K_{St} values, which are of critical importance for design of protective measures, are the same in both apparatuses up to values of 700 bar*m/s.

The dust explosion characteristics are, however, dependent on the turbulence of the dust-air mixture in the explosion vessel. Some turbulence in the air suspension is neccessary to prevent dust particles from depositing. The turbulence has an important effect on the explosion propagation velocity. The delay time between introducing the powder into the vessel and the moment of ignition determines the degree of turbulence in the dust cloud when the explosion takes place. A longer delay time results in a lower degree of turbulence. The test procedure is described in the ISO 6184/1 standard [3]. The standard is widely adopted to enable comparable explosion testing and the design of safety measures (e.g., venting, rupture discs) rely on data produced by standard testing procedures. The ISO standard is, however, valid only at ambient initial pressure.

Testing at high initial pressures complicates the procedure significantly. The amount of dust to be introduced into the vessel increases linearly with the initial pressure. Double dust containers and a special rebound nozzle have to be used to assure the uniform dispersion of dust. With a coarse and inhomogenous material like wood dust the size of the apparatus becomes even more critical. Usually large size 1 m³ vessels are recommended to make the dispersion of the dust into the vessel more easy, thus reaching an acceptable level of turbulence.

2.3   The effect of temperature and pressure

Dust explosions occuring at elevated temperatures tend to exhibit lower maximum explosion pressures than those occuring at ambient temperature. Bartknecht [4] gives a linear relationship between the resiprocal temperature and the P_{max}:

$$\frac{P\text{max}}{P\text{initial}} \sim \frac{T\text{max}}{T\text{initial}}$$

where T is the absolute temperature. However, the relationship between the initial temperature and the rate of pressure rise is less clear [2]. Proportional as well as inverse proportional relationships between temperature and K_{St} are reported in the literature.

Initial pressure and dust explosion indices are closely related. P_{max} is said to be proportional to the inital pressure . This holds true also for K_{St}, but only up to 3 - 4 bar, after which a levelling off can be observed [5]. However, no results of experiments over an initial pressure of about 6 bar have been reported. Explosion tests carried out with peat dust indicate that the K_{St} value is proportional to the initial pressure only up to about 4 bar, and then levels off [1].
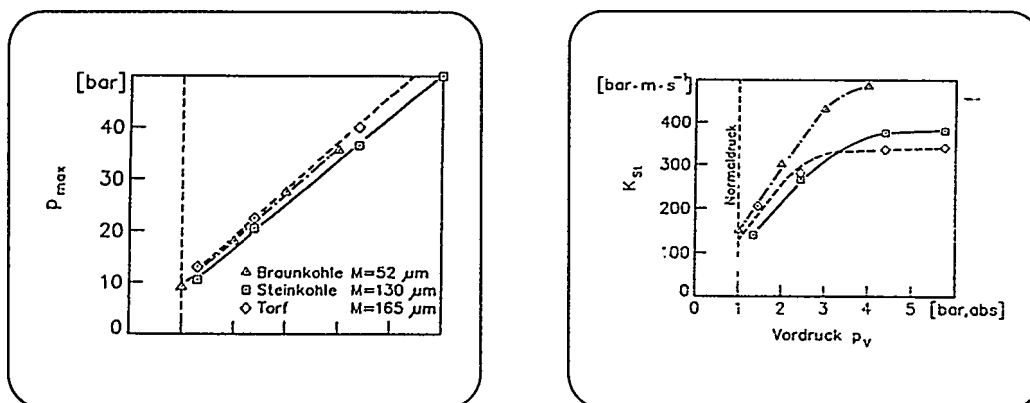
Figure 3. P_{max} and K_{St} as a function of initial pressure. Lignite, coal and peat [5]. .

2.4 Limiting oxygen content

The limiting oxygen content is defined as the oxygen concentration at which an explosion is no longer possible. The limiting oxygen content of combustible dust varies quite significantly, values between 5 and 16 % have been reported. The inert media also influences the limiting oxygen content. Carbon dioxide is a slightly more effective supressant than nitrogen, allowing about 20 % higher LOC values.

The effect of pressure on limiting oxygen content is of special interest in fuel feeding systems. Very few measurements have been reported and the pressure level is restricted to 1 - 6 bar. The reported results are to some extent contradictory, as can be seen in Figure 4 [5]. An increasing temperature reduces linearly the limiting oxygen content [5]. A reduction of 4 - 5 percentage units was observed for forest residue dust, when the temperature was increased from ambient to 200 °C [1].
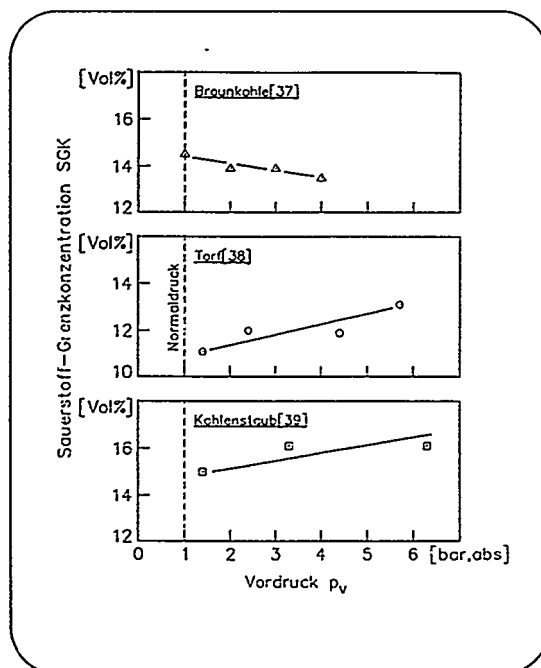

Figure 4. The effect of initial pressure on the limiting oxygen content [5].

3 SURVEY OF THE EXPLOSION TEST FACILITIES

3.1 Background

Until recently the quantative studies carried out on dust explosions were based on relatively moderate initial pressures of up to 4 bar. Most of the institutes and companies offering dust explosion testing relay on small (20 litre) or large (1 m³) vessels with a working pressure of 50 - 60 bar. The large vessels are in many cases equipped with a rupture disc. In these vessels the minimum oxygen content to facilitate an explosion can be measured at even higher initial pressures.
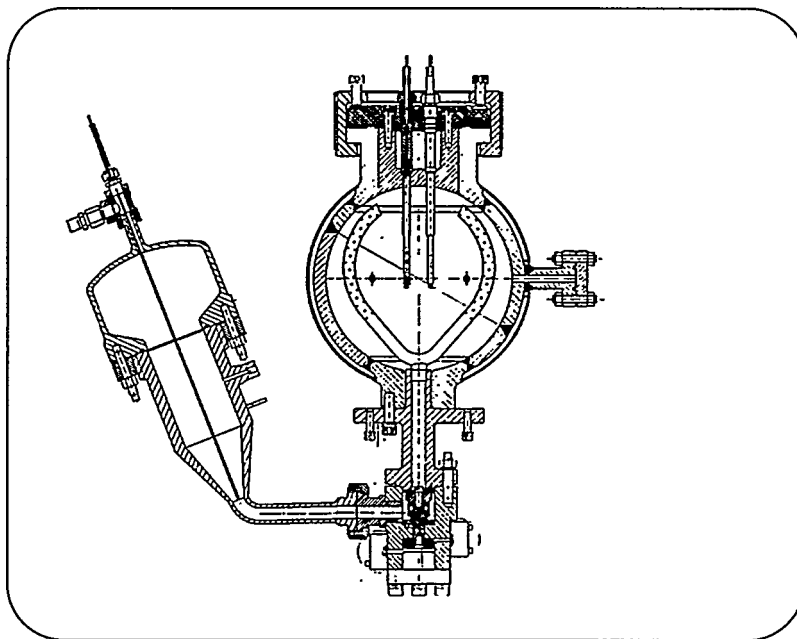
Figure 5. The high-pressure, high-temperature 20 litre sphere [2].

A summary of a fact-finding tour to potential performers of dust explosion tests in May 1993 is presented in the following. The aim was to survey possibilities of various institutes to carry out dust explosion tests at high pressure using the same biomass dust as that used in the experiments at DMT in 1992.

3.2 TNO, Prins Mauritz Laboratory, the Netherlands

TNO has, together with the Delft University of Technology, developed unique pressurized dust explosion equipment of 20 litre in volume, Figure 5 [2]. The spherical vessel can be heated to about 200 °C and pressurised with different gas mixtures. The vessel was tested with gas explosions during 1993 and high-pressure coal dust explosion tests were conducted during 1994.

It was emphasized in the discussions with TNO, that the feed of material into the pressurised vessel and the control of the achieved level of turbulence are the greatest difficulties in dust explosions. The level of turbulence affects the rate of pressure rise, but not significantly the pressure of explosion. The level can in principle be regulated by ignition delay and by the pressure difference between the dust container and the explosion vessel. The level of turbulence is also affected by particle size. It was recommended that the dust should be sieved further to <63 μm if the test had to be carried out in a 20 litre bomb. The experiments with unsieved dust ($d_{50} = 0.22$ mm) should be carried out in a 1 m^3 bomb.

It was concluded that the dust can be fed from the blasting vessel into the bomb at 20 bar differential pressure, as recommended in the standard, or at a higher, 20-fold differential pressure, when a more complete turbulence can be reached. The last-mentioned alternative might correspond best to the "worst" case, i.e., the highest characteristic values could be reached. The dust container can be pressurized to 210 bar. If blasting at 20 bar differential pressure can be carried out, the results would represent an explosion at this level of turbulence. DMT applied 30 bar differential pressure in its experiments.

The effect of turbulence on explosion characteristics will be studied by TNO within an extensive EEC project over the years 1994 - 1997. The parties of the project will be TNO, INERIS, Stuvex, LOM, the coordinator being British Materials Handling Board MBHB.

3.3   Fike Europa, Belgium

Fike Europa is an affiliate of an American company. The company conducts dust explosion tests with a 20 litre sphere according to ISO 6184/1 in the United States. The working pressure of the test vessel is 100 bar, and accordingly an initial pressure of 10 bar can be achieved with the equipment of Fike. Only tests at ambient temperature can be performed. If the oxygen content is reduced to 8 - 14 % tests could be carried out at higher initial pressures. The level of turbulence could be chosen to reach in principle the same conditions and characteristic values as in the tests of DMT at 1 and 4 bar.

3.4   INERIS, France

The equipment of INERIS was located in a rock cave in the test area. The 1 m^3 vessel is cylindric. According to the representative of INERIS it is easier to achieve a sufficient level of turbulence in this kind of vessel than in a ball. Dust explosion tests had been carried out with a Spanish lignite grade at 16 bar pressure on request of Escatrone PFBC project. However, the results were not available in public. The equipment cannot yet be heated, but heating will be installed probably in 1993.

The dust is fed into a vessel located inside the equipment. It is then discharged from the vessel via a valve into a bomb. There should be no difficulties in dispersing the dust. The optimum dust concentration would be determined at normal pressure and this concentration would be used in the tests at pressure.

3.5   LOM, Spain

Laboratorio Oficial J.M. Madariaga is a small research centre within the Polytechnical University of Madrid and is supported by equipment and personnel resources of the university. Safety-technical characteristics of coal and lignite have been studied in connection to the Escatrone power station.

LOM has a 1 m^3 spherical vessel constructed by Chilworth Technology, Great Britain. The working pressure is 150 bar and the designed maximum pressure 225 bar. The vessel is equipped with a rupture disc designed to act at 180 bar. Depending of the explosibility characteristics of the material tested, the initial pressure of 12 bar may be considered an usual value, although initial pressures of 16 or 18 bar can easily be reached. The vessel has a water cooling jacket, and it is not possible to reach higher temperatures than 45 °C.

LOM has recently undertaken an explosion study of sub-bituminous coal mixed with limestone [6]. Tests have been carried out at 12 bar initial pressure in air atmosphere and in an atmosphere with reduced oxygen content. One of the objects of the study was to evaluate the inert behavior of the limestone addition. Combinations of limestone/oxygen ranges within which an explosion is possible/not possible/uncertain were identified. Maximum explosion pressures over 100 bar and rate of pressure rise over 700 bar/s were measured.

4.   DUST EXPLOSION TEST PROGRAMME

4.1   General

Based on results from the survey, it was decided to proceed with the dust explosion testing in two steps.

1.   To perform explosion tests in a large 1 m^3 vessel to determine P_{max}, K_{St} and limiting oxygen content (LOC) at elevated pressures.

2.   To perform tests in a 20 litre sphere to evaluate the influence of both elevated pressure and temperature.

The tests of Step 1 were to be performed by LOM during January-April 1994. After the tests in the large vessel the testing would be proceeded with a somewhat reduced programme at elevated temperatures using the equipment available at TNO.

Testing was commenced at LOM according to the time schedule. Difficulties with the dispersion of the biomass dust into the 1 m^3 vessel at high initial pressures lead to substantial delay in the test programme. The testing was completed according to the specified programme in late November 1994 and reported in February 1995 [9].

4.2   Test programme at LOM

The test programme consisted of two parts, phase A) and phase B). The programme started with phase A) and proceeded with phase B), after the first phase had been successfully completed. The programme is described in Table 1.

Table 1. The explosion test programme at LOM.

	Vessel	1 bar	10 bar	15 bar	
Phase A. Explosion characteristics	20 litre	P_{max} dP/dt, K_{St}			
	1 m³	P_{max} dP/dt, K_{St}	P_{max} dP/dt, K_{St}	P_{max} dP/dt, K_{St}	
	Vessel	1 bar	5 bar	12 bar	18 bar
Phase B. Inerting tests	20 litre	LOC			
	1 m³		LOC	LOC	LOC

4.3   Preparation of dust sample

The biomass dust consisted of forest residue chips milled by a disk refiner two times to obtain a sufficient fine particle size. About 400 kg of this milled biomass dust was sent to LOM for testing. The forest residue chips were originally delivered by Vattenfall from Sweden for the dust explosion tests carried out by DMT in 1992.

In late August 1994 a second batch of 300 kg of forest residue chips was delivered to LOM. Although not of the same origin as the previous batch, this fuel was both visually and chemically almost identical to the first batch. This forest residue was chipped and dried for gasification tests in the pressurised PDU rig at VTT Energy in Espoo, Otaniemi. The sample of chips was prepared for the explosion tests by LOM.

In the first stage of testing the dust in the 20 litre vessel in ambient pressure and in the second stage when initiating the tests in the 1 m³ sphere, it was noticed that the biomass dust was very difficult to introduce into the vessel. Due to agglomeration and blocking of the the dispersion valve irregular dispersion of the dust cloud was obtained. For higher dust concentrations in elevated initial pressure, total obstructions in the dispersion valve was found. The non-homogeneous nature of the biomass dust, its very low density and the needle-shaped fibres were the causing factors for this behaviour.

After the initial tests it was decided to mill the dust even finer in order to eliminate the fibrous nature of the dust. A small oscillating hammer mill, Figure 6, was used to produce a fine fraction (> 50 % of the whole sample) collected in the bag filter.

The same hammer mill was used to prepare the second dust sample. In this case the sample had to be dried further to obtain a sufficiently fine particle size.
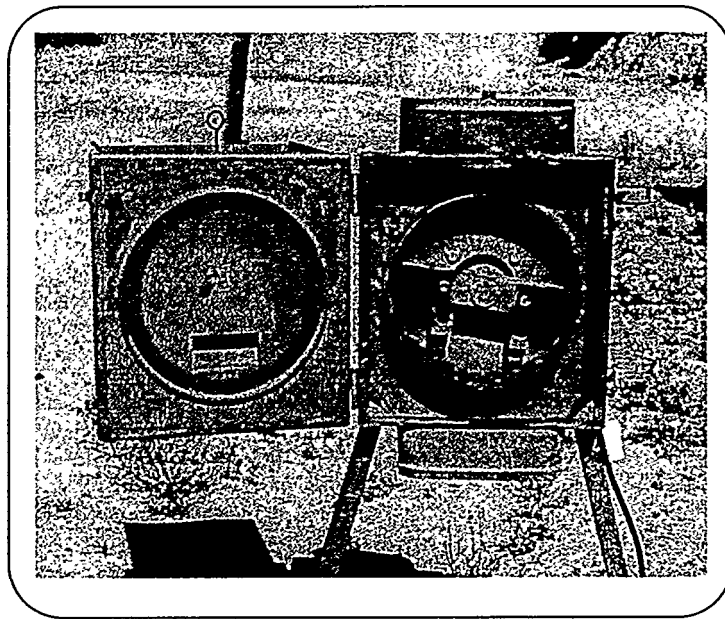
Figure 6. Oscillating hammer mill, LOM.

4.4   Chemical and physical properties

The first dust sample used in the ambient pressure testing was denoted as VTT-1-F and the second sample used in the hyperbaric testing was denoted VTT-3-F. The chemical analyses of these samples were virtually identical. The final particle size of the second sample was slightly coarser due to the fact that this sample was not precrushed with the disk refiner.

The chemical and physical analyses performed by VTT and LOM are presented in Table 2.

Figure 7 shows a microscopic view of the VTT-1-F sample used in the explosion tests. Note that the squared paper seen at the bottom of the photografy corresponds to 1 mm x 1 mm squares.

Table 2. Analyses of biomass dust.

	VTT-1-F	VTT-3-F
Proximate analysis		
Moisture, %	6.0	1.8
Ash, % d.b.	2.9	2.2
Volatiles, % d.b.	78.0	79.5
Ultimate analysis		
C-content, % d.b.	53.1	52.3
H-content, % d.b.	5.9	6.0
N-content, % d.b.	0.3	0.6
O (balance), % d.b.	40.7	41.1
Paticle size, d_{50}, µm	200	275

Figure 7. Microscopic view of the dust sample VTT-1-F.

5 EXPLOSION CHARACTERISTICS

5.1 Atmospheric data

5.1.1 Explosion data

A complete set of explosion tests was carried out for two biomass samples, the first sample being a forest residue sample in its original state (milled in a disk refiner), denoted VTT-1-R, and the second one, VTT-1-F, the same sample after further milling in the hammer mill at LOM. The results are presented in Table 3.

Table 3. Explosion data.

	VTT-1-R $d_{50} = 280$ µm	VTT-1-F $d_{50} = 200$ µm
Minimum ignition temperature on a layer	320 °C	320 °C
Minimum ignition temperature in a cloud	420 °C	400 °C
Minimum explosible concentration	125 g/m^3 (Hartmann tube) 80 g/m^3 (20 l sphere)	30 g/m^3 (Hartmann tube) 20 g/m^3 (20 l sphere)
Minimum ignition energy	140 mJ	40 mJ
Maximum explosion pressure (20 l apparatus)	8.5 bar(g) (at 1500 g/m^3)	9.1 bar(g) (at 750 g/m^3)
Maximum rate of pressure rise (20 l apparatus)	165 bar/s (at 1250 g/m^3)	400 bar/s (at 2000 g/m^3)
K_{St}-value (calculated according to the cubic law)	44 bar*m/s	108 bar*m/s

The biomass dust shows a very high sensitivity to ignition: it can easily be ignited by a hot surface as well as by electrical sparks of low energy. The dust also presents a high severity of explosion and can be classified as St 1 dust.

From Table 3 it can be seen that the finer dust VTT-1-F shows an even higher sensitivity and severity with respect to ignition and explosion than the coarse dust.

5.1.2 Maximum explosion pressure and rate of pressure rise

Figures 8 and 9 show the variation of maximum explosion pressure P_{max} and maximum rate of pressure rise (dP/dt) with dust concentration. Dispersion problems with the coarser biomass dust can be seen in the measurements as a higher degree of scatter (Figure 8). Detailed results are presented in Appendix 2.
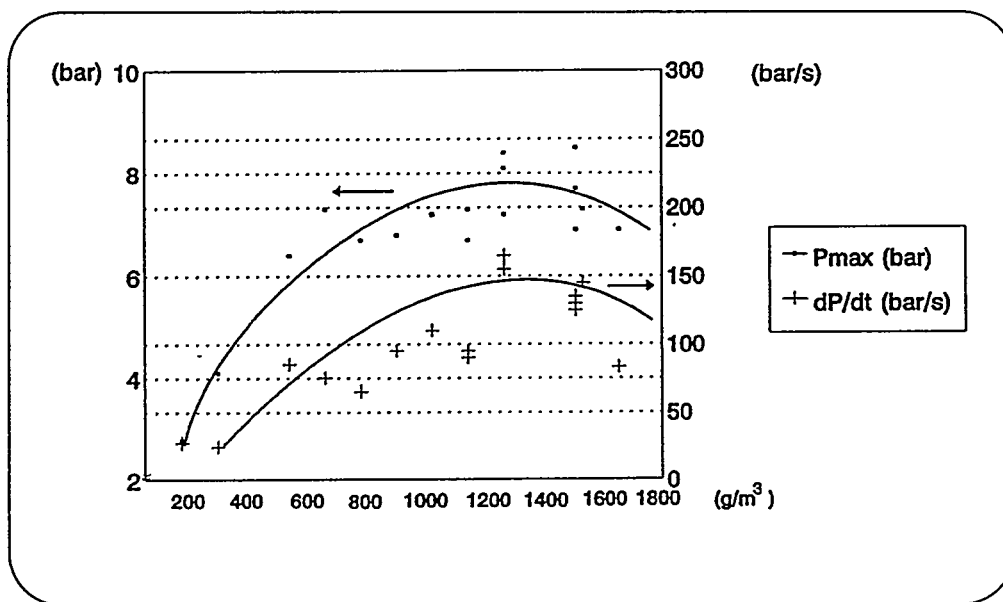

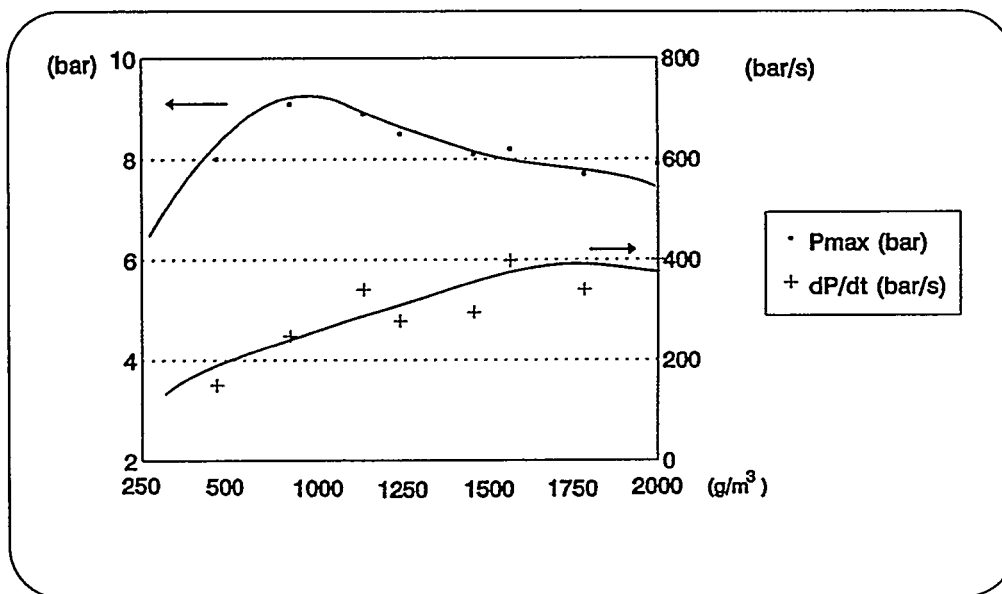*Figure 8. Explosion data Pmax and dP/dt of sample VTT-1-R.*

Figure 9. Explosion data Pmax and dP/dt of sample VTT-1-F.

5.2   Elevated initial pressures

5.2.1   The 1 m³ explosion test facility

The experimental equipment for the hyperbaric tests consisted of a spherical 1 m³ pressure vessel interconnected with a dust charging vessel which operates under microprocessor control. After charging the test dust and pressuring the vessels, a fast acting detonator valve opens to disperse the dust into the main vessel. At a predetermined time, in this case 900 ms, two 10.000 J chemical ignitors located in the centre of the sphere are activated to initate the explosion. Two pressure tranducers monitor the pressure/time record and an A/D converter transfers the data to the hard disk of a computer. In the inerting tests the main vessel and the dust container are pressurised with the relevant oxygen-nitrogen mixture. The ignition time delay and the pressure difference between the dust container and the sphere determine the degree of turbulence obtained with a certain dust during the testing. The standard pressure difference used in atmospheric explosion tests is 20 bar.

The dispersion problem found in the atmospheric tests suggested, that more serious troubles could be present in the hyperbaric tests. It was also obvious that the dust discharge container was not large enough to facilitate the required amount of dust for the pressure tests. Optimum dust concentration could not be reached at elevated pressures. The use of an internal discharge by means of a plastic bag in the explosion vessel was considered. VTT recommended the installation of a second discharge container. When the testing time was extended to the beginning of September 1994, LOM decided to enlarge the original container from 20 to 25 litre and install a second one. Both containers were equipped with a new redesigned dispersion valve providing a larger cross section between the containers and the explosion vessel. Both valves were connected to synchronise the firing of the detonators. To disperse the dust, two "rebound nozzle" type dispersers were used. The explosion vessel and the dust containers are shown in Figure 10.

5.2.2 Explosion pressure and rate of pressure rise

Explosion tests were conducted in the 1 m³ sphere at initial pressures of 1, 10 and 15 bar. The differential pressure pulse used for dust dispersion ranged from $\Delta P = 20$ bar to $\Delta P = 35$ bar. One or two dust deposits were used, as stated in the tables of results. The explosion tests were performed with 6 - 10 different dust concentrations at each pressure level. The detailed results are presented in Appendix 3. The variation of P_{max} and dP/dt with dust concentration at 1, 10 and 15 bar is shown in Figures 11 - 14, respectively.

Table 4 summarises the results, presenting maximum explosion pressures (MEP) and maximum rates of pressure rise (MRPR) as the maximum values of P_{max} and dP/dt, respectively, in all the tests carried out at the different levels of initial pressures and under the different testing conditions (number of deposits and differential dispersion pressure).
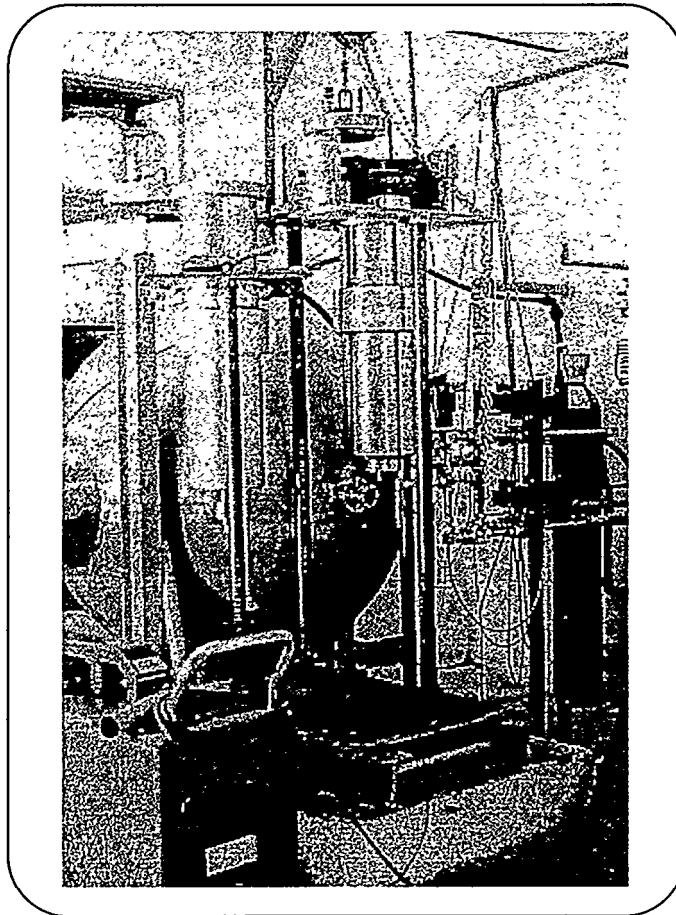
Figure 10. Hyperbaric test vessel equipped with two enlarged dust containers.
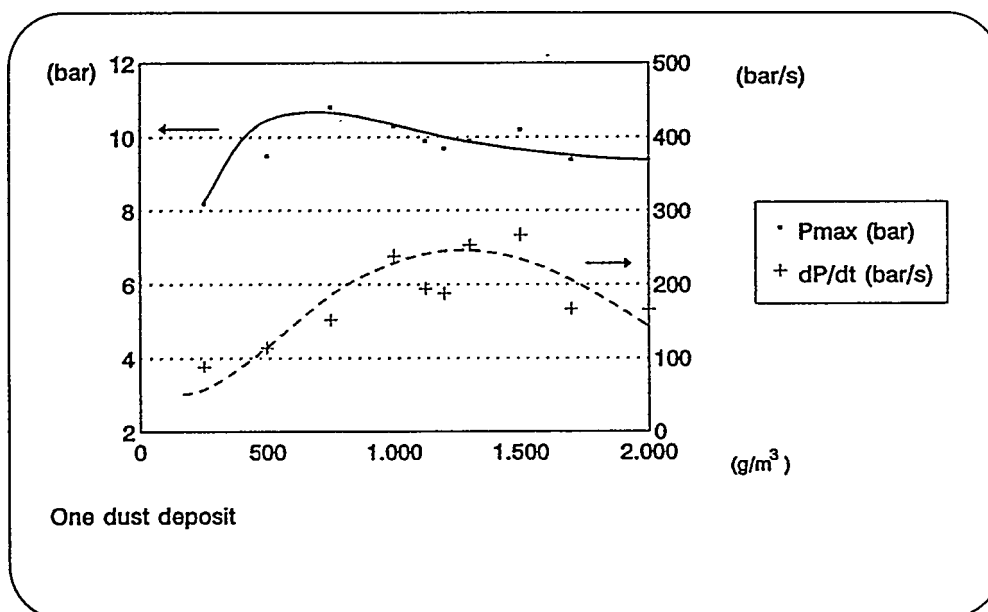
*Figure 11. Variation of P_{max} and dP/dt with dust concentration
for biomass dust in the 1 m^3 vessel at atmospheric pressure.*
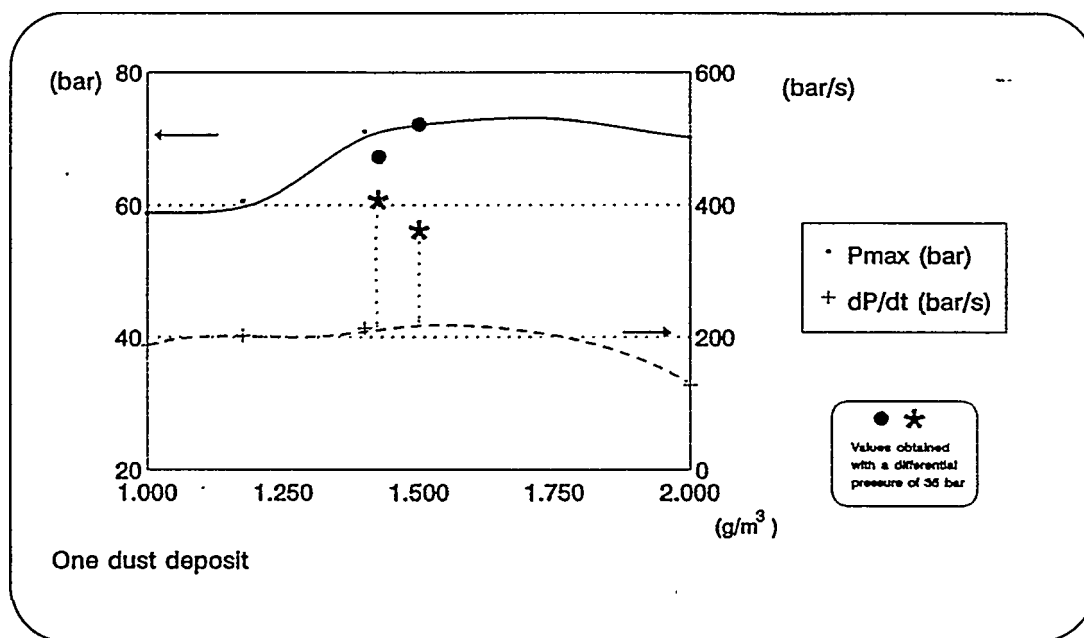
Figure 12. Explosion data for biomass dust. Initial pressure 10 bar. One dust deposit.
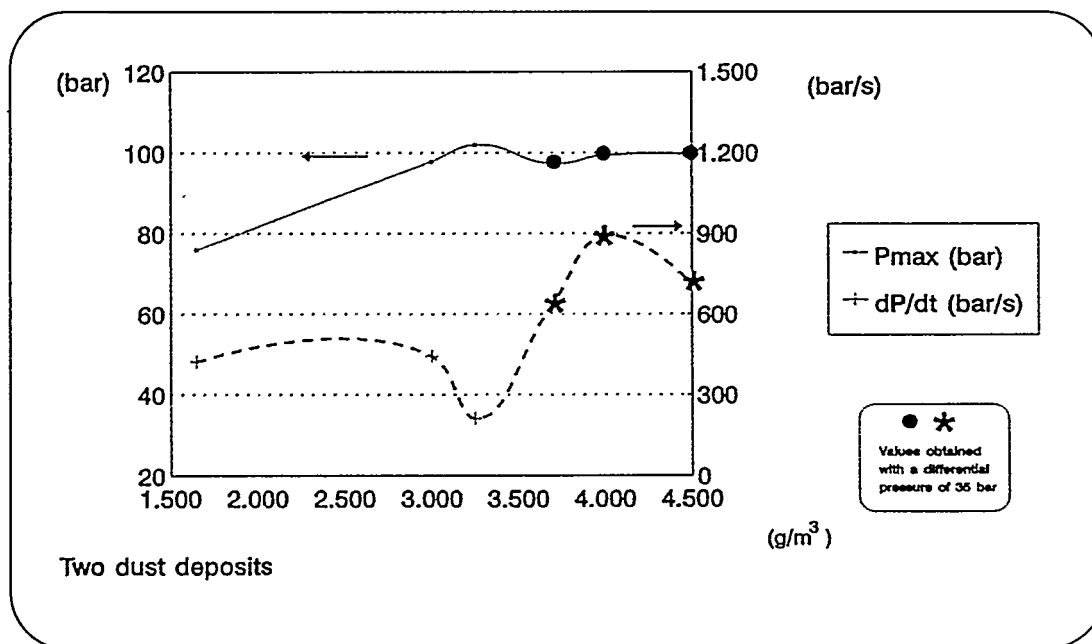
Figure 13. Explosion data for biomass dust. Initial pressure 10 bar. Two dust deposits.
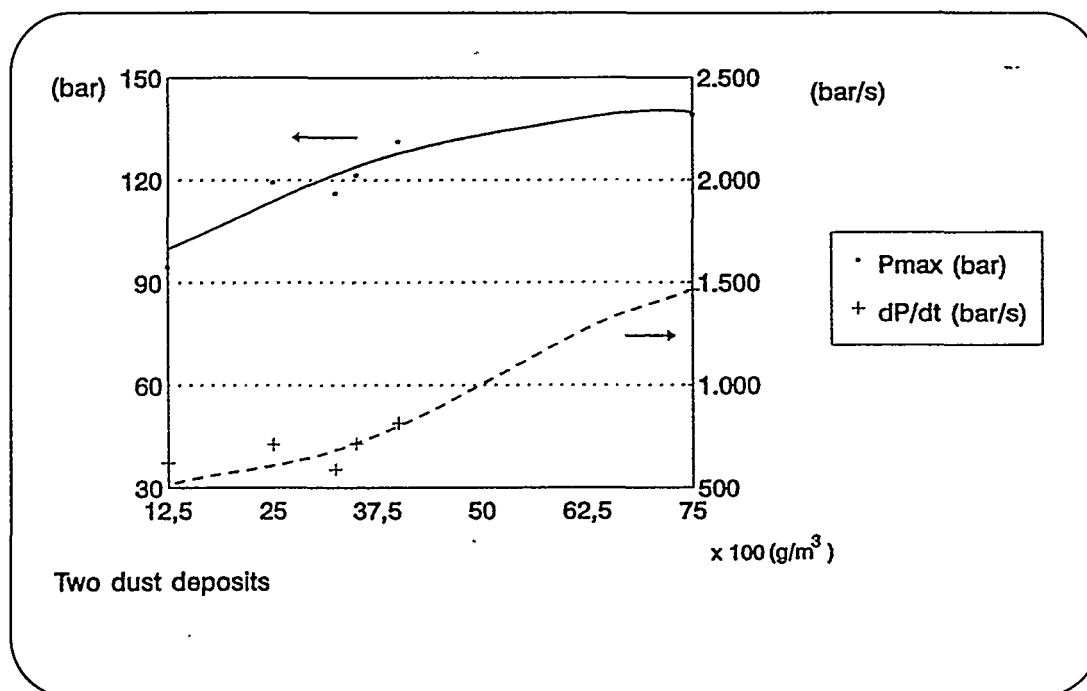
Figure 14: Explosion data for biomass dust. Initial pressure 15 bar. Two dust deposits.

Table 4. Maximum explosion pressure and rate of pressure rise at different initial pressures.

P_{ini} (bar(a))	MEP (bar(a))	Conc. (g/m³) for MEP	MRPR (bar/s)	Conc. (g/m³) for MRPR	Number deposits	Pressure diff. (bar)
1	11.8	750	267	1 500	1	20
10	71	1400	213	1400	1	20
10	71.7	1500	406	1425	1	35
10	102	3250	442	3000	2	20
10	99.9	4500	890	4000	2	35
15	139	7 500	1 462	7 500	2	30

5.2.3   Comparison with previous results

The maximum explosion pressure and rate of pressure rise are shown in Figures 15 and 16 together with results obtained in previous studies with peat and forest residue dust [1]. It should be borne in mind that no mathematical regression can be made due to a small number of results and these graphics should be regarded as a manifestation of the explosion trends of the biomass sample.

The tests at 10 bar were carried out using both one and two dust container. The differential pressure between the dust containers and the explosion vessel was also varied from 20 to 35 bar. This resulted in two different cases of turbulence, "high turbulence" and "low turbulence" levels. The level of turbulence influenced the maximum explosion pressure obtained and affected the rate of pressure rise significantly. The maximum explosion pressure behaved as expected, the explosion pressure increased proportionally to the initial pressure. The rate of pressure rise (described by the K_{St} value) increased rapidly with the initial pressure and reached extremely high values especially in the case of "high turbulence". Contrary to expectations on the basis of earlier experience, no levelling off at high initial pressures was observed. As can be seen, the degree of turbulence affected the rate of pressure rise much more than the explosion pressure itself.

Figure 15. Maximum explosion pressure as a function of initial pressure.

Figure 16. Maximum rate of pressure rise as a function of initial pressure.
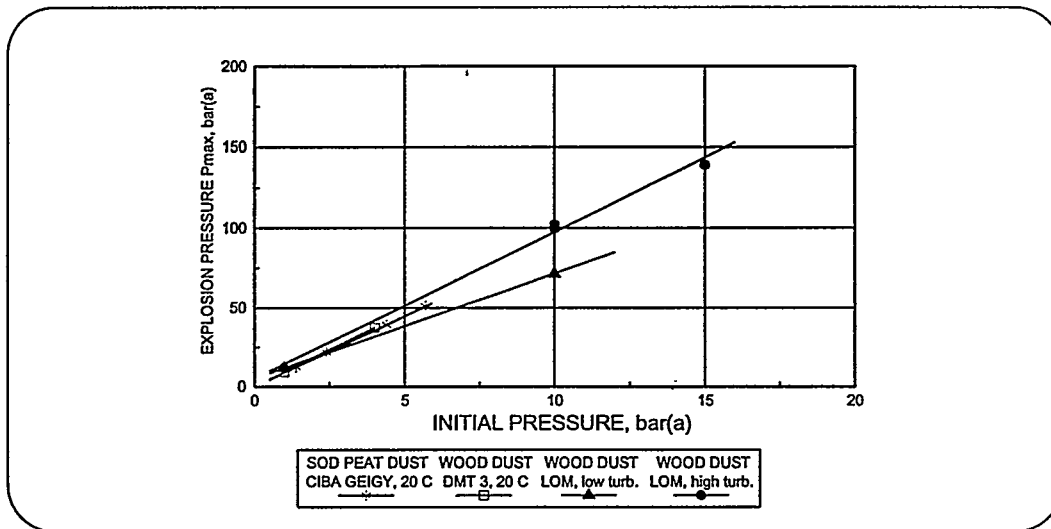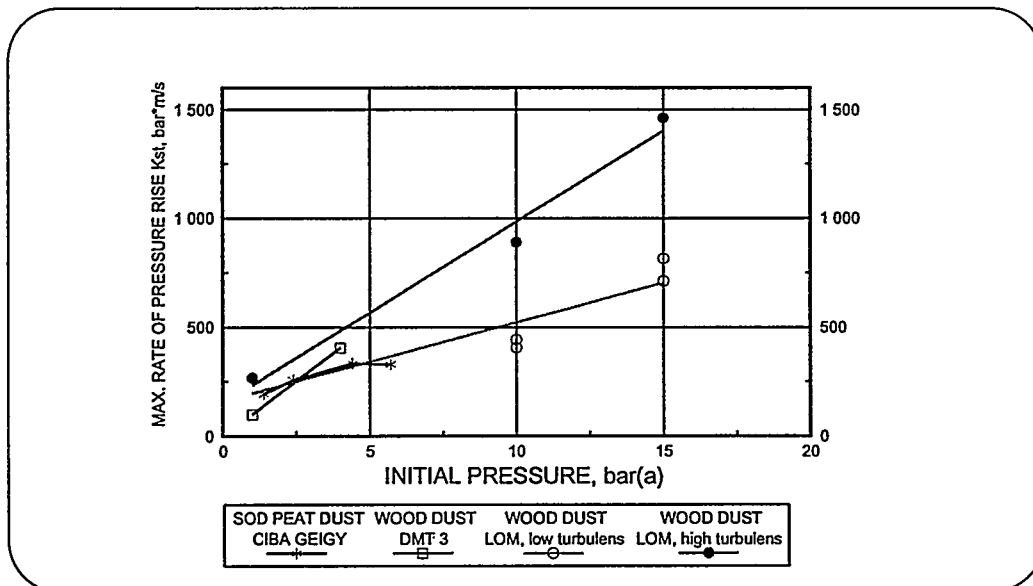
6   INERTING TESTS

6.1   Limiting oxygen concentration at atmospheric pressure

The limiting oxygen concentration (LOC) was determined in the 20 litre sphere following the standard test procedure used by numerous European laboratories. Nitrogen was used as inert gas. The required nitrogen-air mixtures were produced with the partial-pressure procedure. Prior to the tests, the composition of these mixtures were checked by means of an oxygen detector Sieger model OXD-2M. The observed reaction behaviour in 20 litre sphere was considered a non explosion case, if the measured overpressure was less than 2 bar.

A possible limitation of the 20 litre vessel is related to the explosion limits, especially the determination of the limiting oxygen content. The ignition energy has a strong effect on the development of the whole explosion. The sensitive bahavior of the laboratory equipment in comparison with the large vessels is due to the influence of the ignition source. The pyrotechnic ignitors used for the dust explosion testing have an energy content of 10 000 J and present a point source in the 1 m^3 vessel. In the 20 litre equipment, however, they affect the whole explosion volume once ignited. Therefore, the limiting oxygen concentration values obtained in the 20 litre sphere have to be adjusted according to the equation below, presented by Ch. Cesana and R. Siwek, for the standard 1 m^3 vessel before they are suitable for practical application. The correlation between LOC values in both vessels was obtained in a comparative study of a number of dusts [5].

*min O_2 (20 l apparatus) * 1.64 = min O_2 (1 m^3 vessel)*

The limiting oxygen concentration was determined for the fine biomass dust VTT-1-F only. Seven oxygen levels were tested with dust concentrations ranging from 30 g/m^3 to 1 000 g/m^3. Figures 17 and 18 show the explosibility reduction produced by progressive inerting of the atmosphere.

From the tests it can be concluded that the limiting oxygen concentration measured for the fine biomass dust is 5 % in the 20 litre vessel. According to the correlation presented above, the expected value in a standard 1 m^3 vessel should be 8.2 %. As the oxygen content was reduced, the duration of combustion increased, from less than 0.1 s (21 % oxygen) to more than 0.3 s, reaching 0.5 s in some cases.

6.2   Elevated initial pressures

6.2.1 Experimental procedure

The test procedure was initially designed according to the scheme presented in Figure 19. The initial value of 8 % oxygen was chosen on the basis of the value obtained in the 20 l apparatus (5 %) and the correlation presented above, which gives a value of 8.2 % as the expected value of the limiting oxygen concentrationin a 1 m^3 vessel.
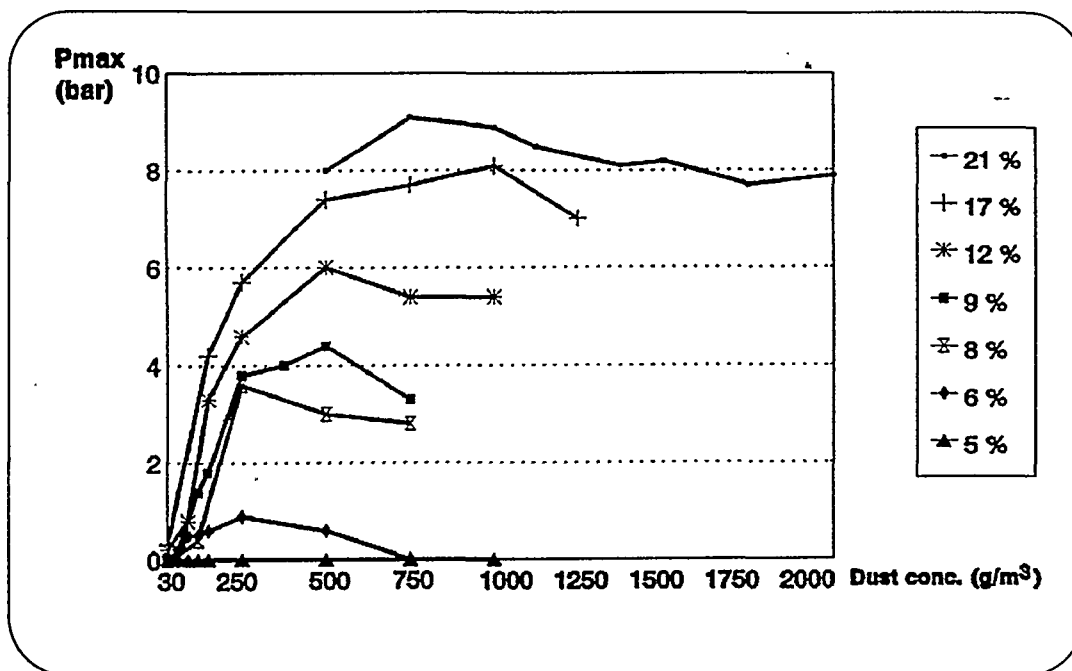
*Figure 17. Maximum explosion pressure as a function of dust concentration
and oxygen content.*
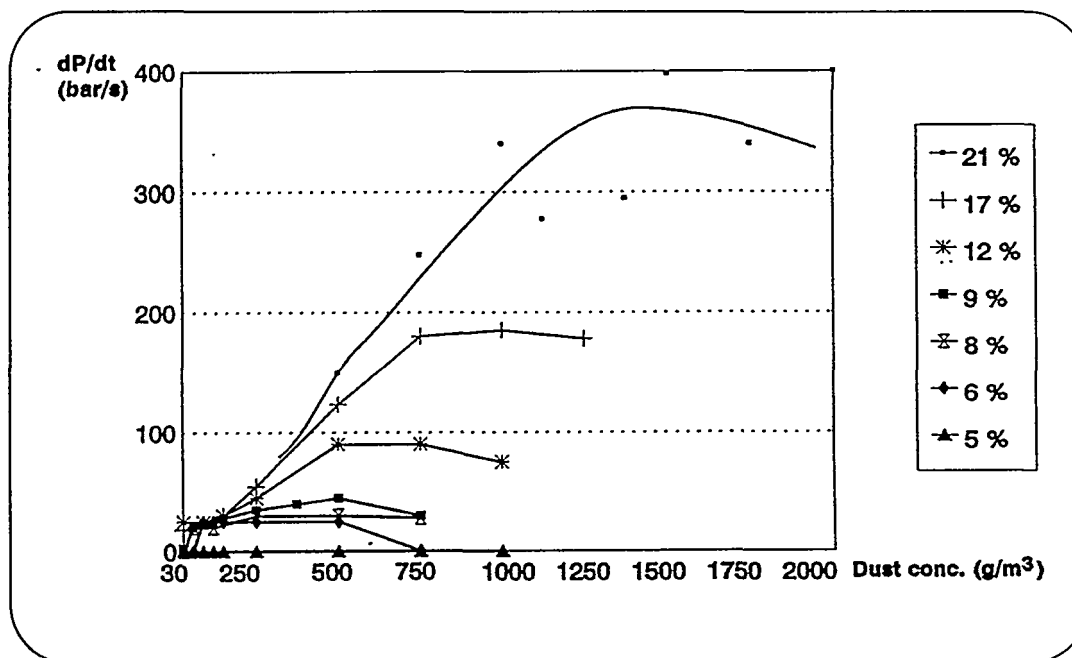
*Figure 18. Maximum rate of pressure rise as a function of dust concentration
and oxygen content.*
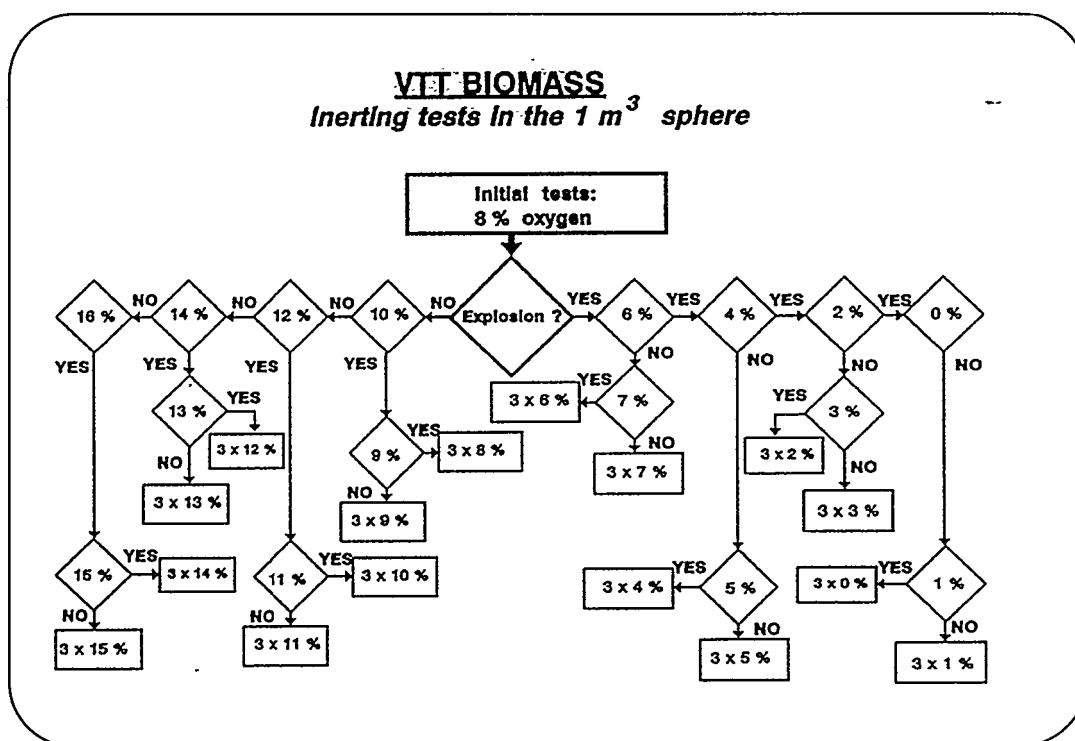
Figure 19. Testing procedure for inerting with nitrogen.

Dust concentration for inerting tests must be low since the reduction of the O_2 content in the air first affects the upper fuel-rich limit.

Once the limiting percentage of oxygen is found, three additional checking tests should be carried out. The checking tests are carried out for three different dust concentrations. If an explosion occurs in a non-explosion checking test, a new series of three checking tests should be carried out by lowering the oxygen content by 1 percentage unit.

All the inerting tests at elevated initial pressures were carried out using two dust deposits. The differential pressure for dust dispersion ranged from $\Delta P = 20$ bar (for $P_i = 5$ bar) to $\Delta P = 26$ bar (for $P_i = 18$ bar).

6.2.2 Results

The results are summarised in Table 5. The results are presented in detail in Appendix 4. Figure 2 gives a graphical presentation of the results obtained in the 5 bar tests and Figure 21 provides the pressure vs time record of the explosions obtained. The attenuation of the explosion with the reduction of the oxygen content is clearly seen.

A clear increase in the LOC value at increasing initial pressure was observed (Figure 22). This is in some respect contradictory to results reported previously for peat and forest residue dust [1]. The difference in LOC values obtained in the pressure range of 1 - 5 bar is rather

Table 5. LOC values at different initial pressures.

Initial pressure bar	Limiting oxygen content %
1	8
5	9
12	13
18	14
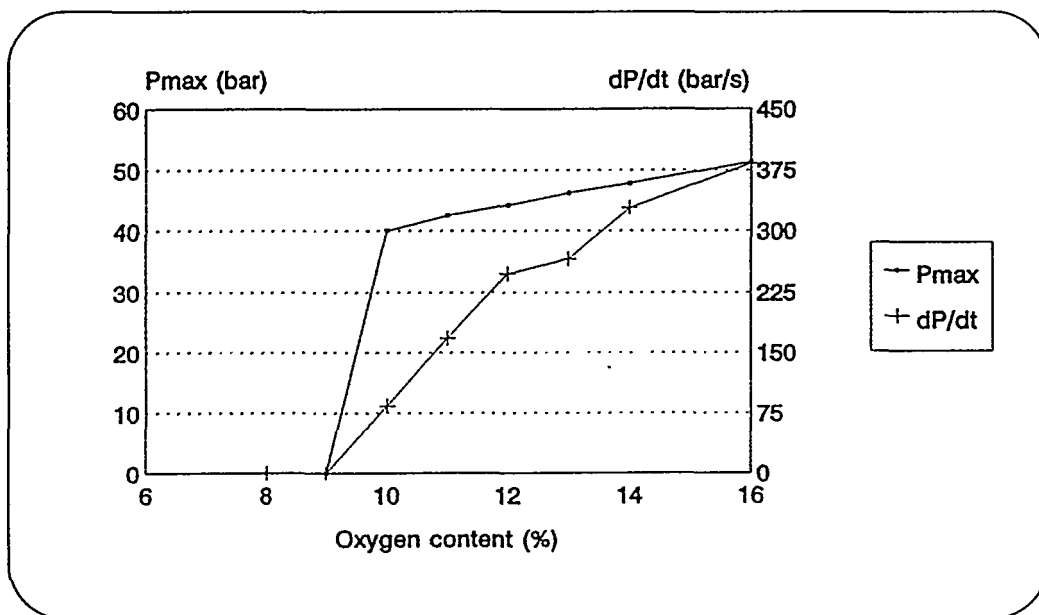
Figure 20. Variation of Pmax and dP/dt with oxygen content at 5 bar initial pressure.

significant. When comparing the LOC values at 1 bar it should be borne in mind that this LOM test was carried out in the 20-litre vessel. Although the corrected value in the 20-litre vessel should correspond to the measurements in the 1 m^3 vessel, the discrepancy could be explained by the use of different test equipment. In the LOC tests at 5 bar the explosion/non-explosion was clearly recorded and the decreasing trend of explosion indices clearly found. At this stage, differences can only be explained by variations in the testing conditions; especially the turbulence obtained for the dust. The difference between 8 and 13 % is fairly significant considering that in industrial applications a safety margin of 2 percentage units from values determined experimentally is generally recommended. The LOC values at lower pressures should be checked, i.e., in connection with continued testing work at TNO.
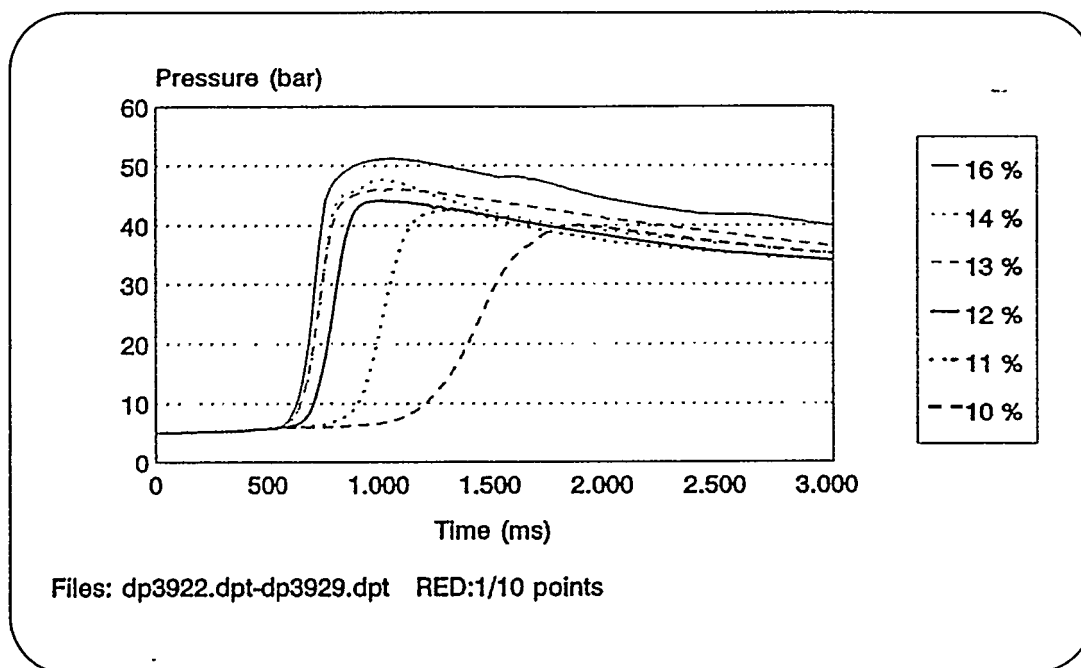
Figure 21. Reduction of explosion curve as oxygen decreases. Initial pressure 5 bar.
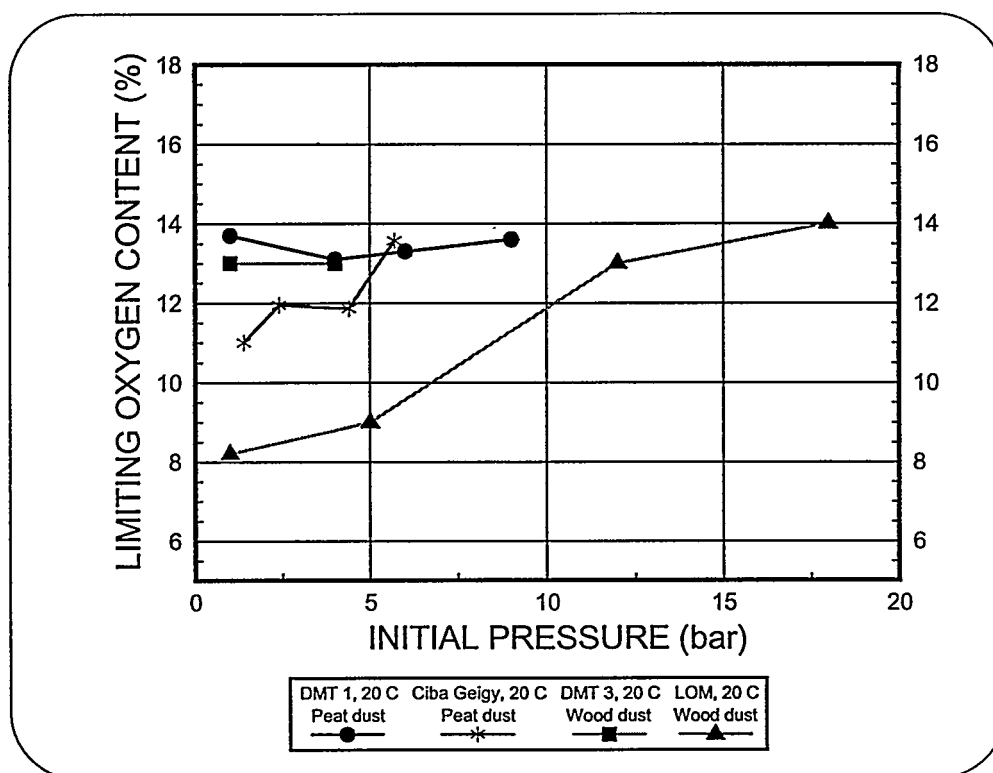
Figure 22. Limiting oxygen content as a function of initial pressure. A comparison between results obtained by LOM and earlier studies on peat and wood dust.

7   DISCUSSION OF RESULTS

7.1   Explosion tests

When discussing the results it is important to bear in mind the specific properties of biomass dust (very low density, inhomogeneous particle size and shape) that results in non-uniform dispersions of the powder and in the formation of irregular non-homogeneous clouds.

The high initial pressures required large amounts of dust to be dispersed into the explosion vessel. As a consequence two dust containers and higher pressure pulses were used. The effects of the variation of the test conditions were:

- an increase in the differential pressure pulse produces a higher degree of turbulence and consequently higher MRPR values
- the same effect (increased MRPR) can be obtained if two separated dust deposits are used instead of discharging the dust through one deposit only
- both conditions, increased differential pressure and doubled discharging capacity can be combined and then explosion data rises notably, as can be seen from test No 78 (15 bar, 2 dust deposits), in which an extremely high explosion pressure gradient was obtained.

The increased turbulence affects the rate of pressure rise much more than the explosion pressure itself. This is because an increase in the turbulence produces a higher mobility of particles, the access of oxygen to the surface of the dust particles is promoted and the burning rate rises greatly.

As can be seen in the explosion data curve corresponding to $P_i = 10$ bar and two dust deposits (Figure 13), the explosion pressure is not very affected by the use of a higher dispersion pressure pulse, while the curve of maximum rate of pressure rise clearly offers two different zones: the left side concerns explosion data obtained with $\Delta P = 20$ bar and the right side with $\Delta P = 35$ bar.

In many explosion tests resulting in an explosion, a subsequent remnant fire was produced in the explosion chamber after the explosion.

7.2   Development of explosion

During a "normal" explosion process, the ignition core rapidly grows through the dust cloud producing a self-propagating flame front that generates hot gases at increasing pressures. Figure 22 shows a typical explosion pressure-time curve. After reaching the maximum pressure, hot gases cool very fast and the pressure inside the vessel drops. When the explosion chamber is opened for cleaning after an explosion, it can frequently be observed that an important part of the residue remains unburnt. This is probably due to fast quenching of the combustion front, partly produced by the depletion of available oxygen.
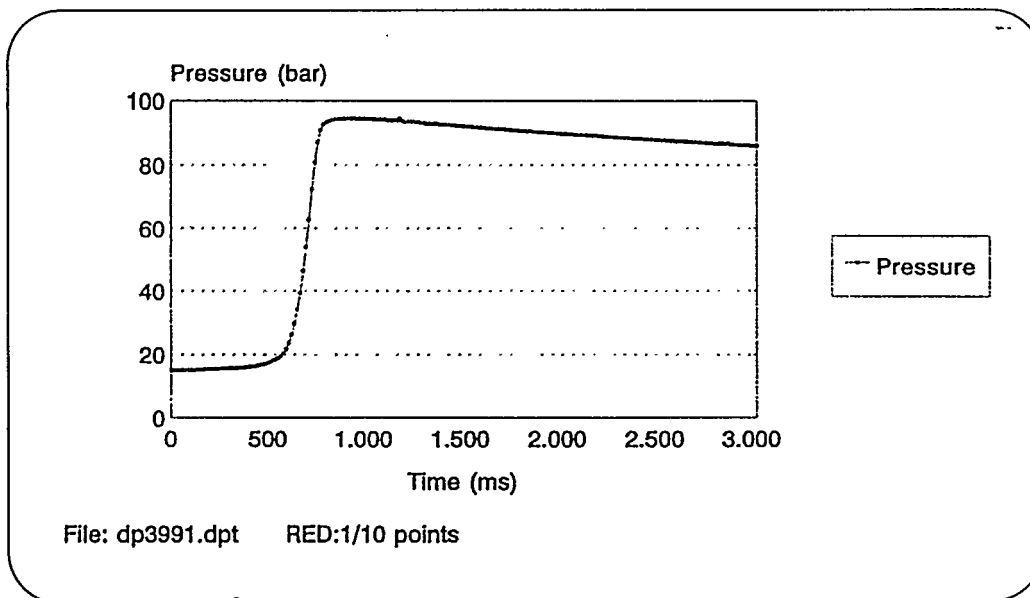
Figure 23. Pressure curve obtained at 1 250 g/m³, P_i=15 bar.

At high initial pressures, the air density increases and more oxygen is available in the same volume. The change in the slope of the pressure curve seen in Figure 23 can be caused by disturbances in the development of the explosion nucleus that affects the flame front propagation and thus produces discontinuities in the rate of explosion rise.

When the quantity of dust inside the explosion vessel greatly increases (more than 3 000 g/m³ can be regarded as heavy loads) homogeneity in the dust cloud is hardly achieved, appearing in zones with different concentration and remarkable spatial gradients. This situation is particularly worse for non-spherical particles (elongated as biomass fibres) and for powders with low density (forest residue).

Due to the inhomogeneous cloud, secondary flame fronts can develop during the propagation of the incipient explosion. This fact is clearly seen in Figure 24, which shows the second pressure pick some 1 100 ms after the first one.

Figure 25 shows the pressure curve obtained in test No 78, in which almost 140 bar and 1 500 bar/s were obtained. The rupture disk as well as the venting duct were completely destroyed. Therefore, the pressure instantaneously falls down to low values.

This explosion was obtained under almost the worst possible experimental conditions: maximum level of turbulence (two deposits, $\Delta P = 30$ bar) and maximum initial pressure (15 bar).
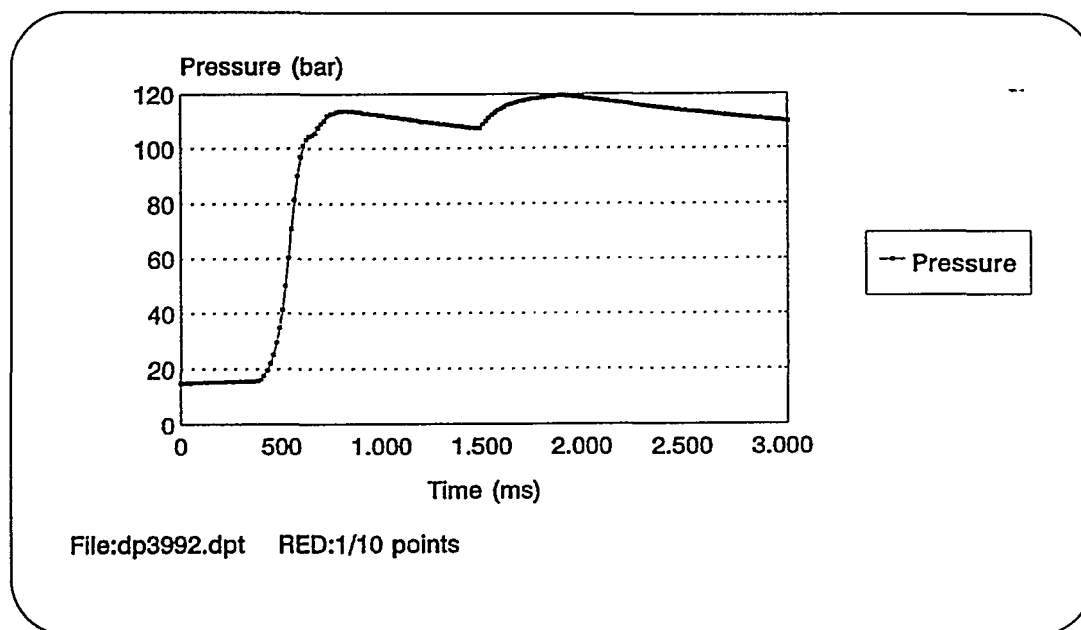
Figure 24. Pressure curve obtained at 2 500 g/m³, P_i=15 bar.
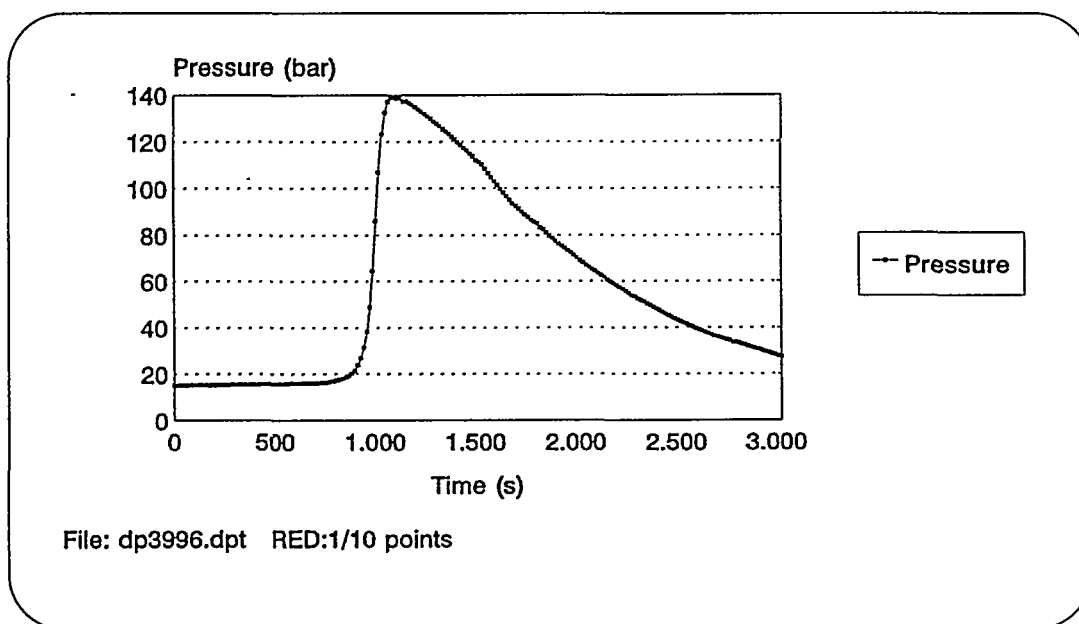
Figure 25. Pressure curve obtained at 7500 g/m³, P_i=15 bar.

The *dust dispersion was completely effective and a* high concentration was obtained (7 500 g/m^3). It is possible that a stronger explosion were obtained if a larger ΔP or higher concentrations were used, but for safety reasons it cannot be found in this test equipment. Although the equipment is designed to withstand even higher explosion pressures (vents actuate at 170 bar), the very high temperatures (>1 600 °C) and the "wild" rate of pressure rise obtained that caused severe damage to the installation advised to abandon the idea of going further.

7.3   Inerting tests

When the initial pressure is elevated, more air and consequently a larger quantity of oxygen is present in the atmosphere contained in the test vessel, so that a reduction of the LOC with the initial pressure would not be surprising. Wiemann [7] has found that increasing the initial pressure from 1 to 4 bar decreases the oxygen limit concentration slightly by 1 %.

On the other hand, some researchers have shown in their experiments that LOC can keep constant when the initial pressure rises: according to Bartknecht [4], over a wide range, the limiting oxygen concentration is independent of the initial pressure. Eckhoff [8] presented results produced by others showing that the maximum permissible oxygen concentration for inerting clouds of a polymer powder was independent of the initial pressure over the range 1 - 4 bar. Previous studies on peat and biomass [1] have revealed a similar tendency.

What LOM has found in this experimental work is not a reduction of LOC nor an independent behaviour of the initial pressure, but an increase of LOC with the starting pressure.

At first sight this behaviour is not easy to explain and seems to be contradictory to previous results obtained by others. First of all it should be noted that as high initial pressures as in these tests have never been reached in other research works.

At very high initial pressures, the surroundings have a higher density due to the larger quantity (mass) of air and also of particles if equivalent mass concentrations are reached. This can lead to a major difficulty in the development of the ignition nucleus and in the propagation of the initial reaction zone. The ignition limit must be displaced towards richer conditions and a larger quantity of oxygen is needed to initiate the combustion and explosion processes.

The possibility of obtaining explosion below the LOC values obtained in this study is certainly remote, although its probability does not equal zero since there are many factors involving the explosion process (initial pressure range, percentage of oxygen, dust granulometry, dust concentration, temperature, moisture, turbulence, ignition energy, etc.) and experimentally it is not feasible to test all possible combinations of factors. In fact, when an explosion was obtained near the oxygen limit at 12 bar and 18 bar of initial pressure, the explosion process developed very mildly (slow deflagration or very fast combustion). This phenomenon was observed in several tests, but the explosion was not registered because it

occurred several seconds after the ignitors were activated. The delay time was about 20 seconds.

In order to register the pressure curve, the record time was expanded to one minute. Figure 26 shows the pressure-time curve for test No. 121 (18 bar, 15 % oxygen). Irregularities (difficulties) can be observed in the development of the curve, and very low rates of pressure rise were produced.

Combustion of biomass at 20 s after injection may not be interpreted as an actual explosion. Most of the dust may have settled down by this time period, and the pressure rise may rather be due to combustion of the dust layer than flame propagation in a dust cloud. However, officially it is only the recorded explosion pressure that determines whether a dust-inert-air mixture is explosible or not. Therefore, and also for practical reasons, it is advisable to consider these slow combustions as real dust explosions.
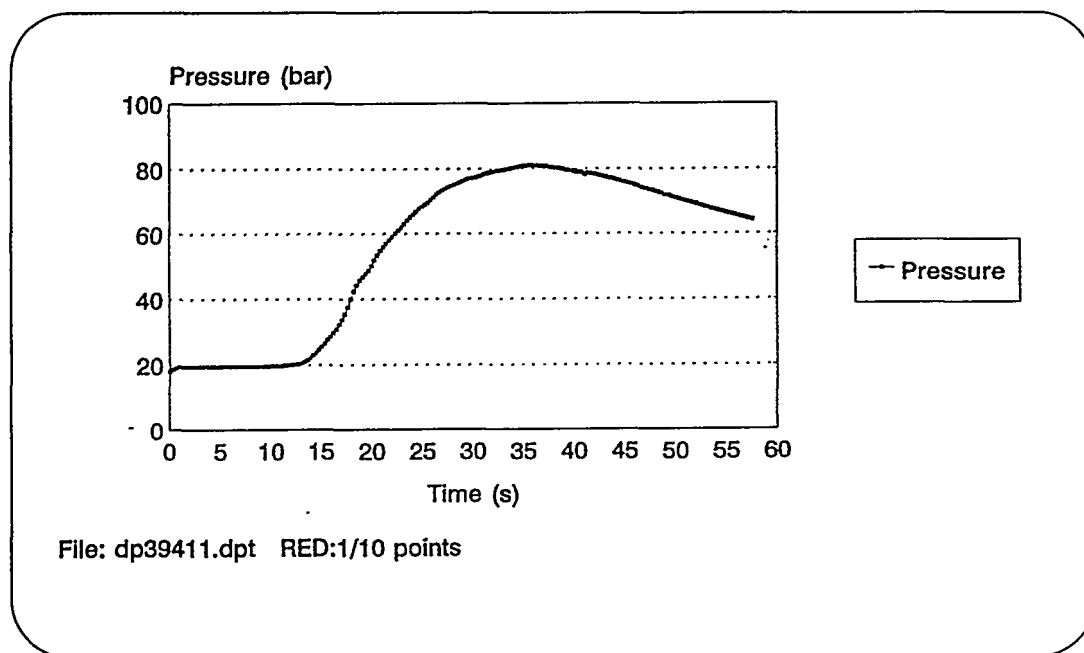
Figure 26. Soft delayed explosion at 18 bar.

8   CONCLUSIONS

The biomass dust tested is very sensitive to ignition and very often it yields a secondary remnant fire.

The intrinsically high explosion severity of the product is greatly increased as the initial pressure rises, and consequently, high temperatures (> 1 600 °C), very elevated explosion pressures (close to 140 bar) and extremely high rates of explosion pressure (almost 1 500 bar/s) can be found for initial pressures of 15 bar.

The limiting oxygen concentration obtained for the biomass dust increased from 9 % at 5 bar to 14 % at 18 bar of initial pressure, explosions having registered above these limits.

The explosion testing of the forest residue dust at high initial pressures involved several experimental difficulties, mainly due to the inhomogeneous character of the biomass dust. As the performer of the explosion tests, LOM is confident of the accuracy of the results. However, some of the results are questionable and should require further research:

-    The explosion indices P_{max} and dP/dt measured at atmospheric pressure revealed surprisingly high values compared with the results reported previously on peat, biomass and coal.
-    The optimum dust concentration may not have been reached in the 15 bar explosion test. Consequently, the corresponding maximum values of explosion pressure and, especially, the rate of pressure rise may not have been obtained, despite the extremely high values measured.
-    The difference between the limiting oxygen contents measured by LOM and DMT is difficult to explain, particularly, as this difference occurs in the low-pressure region, where standard or nearly standard test conditions can be expected.

The reliability of the results is difficult to assess, as there are no test results available, not even for other fuels in corresponding test conditions. There is no standard method available for explosion tests at high pressure, which also hampers the interpretation and comparison of the results. However, the realization of this unique test programme has given valuable data on the rather violent explosion characteristics of forest residue dust and inhomogeneous biomass dust in general at elevated pressure.

On the basis of the very high explosion pressure and rate of pressure rise measured at elevated initial pressures, it is qiute obvious, that designing the feeding bins for total explosion containment is not feasible in practice. Neither can relief venting be used due to the large required vent area and high reduced pressure. Explosion suppression, which involves discharging a suitable agent into the fuel bin near the developing explosion, has been used in atmospheric aplications. The technology is, however, not yet commercial for pressurized systems. Inerting offers a safe alternative, but involves usually high investment and operation costs. The marked retarding effect of inerting on the rate of pressure rise suggests that a combination of partial inerting and suppression may be applicable at high initial pressures. The suppression system and the above mentioned combination have to be demontrated in practice before commersial applications can be expected.

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Maximum explosion pressure and minimum oxygen content
as a function of initial pressure.
Results obtained i earlier studies and the aim of the current project.

LIMITING OXYGEN CONCENTRATION (LOC) IN THE 20 LITRE SPHERE

DUST CONCEN-TRATION (g/m³)	OXYGEN CONCENTRATION													
	21 %		17 %		12 %		9 %		8 %		6 %		5 %	
	Pmax (bar)	dP/dt (bar/s)	Pmax (bar)	dP/dt (bar/s)	Pmax (bar)	dP/dt (bar/s)	Pmax (bar)	dP/dt (bar/s)	Pmax (bar)	dP/dt (bar/s)	Pmax (bar)	dP/dt (bar/s)	Pmax (bar)	dP/dt (bar/s)
30	-	-	0.3	18	0.2	25	0.0	0	0.0	0	0.0	0	0.0	0
60	-	-	-	-	-	-	0.2	20	0.1	20	0.0	0	0.0	0
90	-	-	-	-	0.8	25	-	-	-	-	0.5	25	0.0	0
120	-	-	-	-	-	-	1.4	23	0.4	20	0.5	25	0.0	0
150	-	-	4.2	30	3.3	30	1.8	28	-	-	0.6	25	0.0	0
250	-	-	5.7	55	4.6	45	3.8	35	3.6	30	0.9	25	0.0	0
375	-	-	-	-	-	-	4.0	40	-	-	-	-	-	-
500	8.0	150	7.4	123	6.0	90	4.4	45	3.0	30	0.6	25	0.0	0
750	9.1	248	7.7	180	5.4	90	3.3	30	2.8	28	0.0	0	0.0	0
1000	8.9	340	8.1	185	5.4	75	-	-	-	-	-	-	0.0	0
1125	8.5	278	-	-	-	-	-	-	-	-	-	-	-	-
1250	-	-	7.0	178	-	-	-	-	-	-	-	-	-	-
1375	8.1	295	-	-	-	-	-	-	-	-	-	-	-	-
1500	8.2	398	-	-	-	-	-	-	-	-	-	-	-	-
1750	7.7	340	-	-	-	-	-	-	-	-	-	-	-	-
2000	7.9	400	-	-	-	-	-	-	-	-	-	-	-	-

EXPLOSION TEST AT ELEVATED PRESSURE

Initial pressure 1 bar(a), 1 dust container

Test number	Dust concentration (g/m³)	Pmax (bar)	dP/dt (bar/s)	ΔP (bar)
36	250	8.2	88	20
33	500	9.5	114	20
19	750	10.8	152	20
27	1000	10.3	238	20
31	1125	9.9	194	20
34	1200	9.7	188	20
32	1300	9.9	253	20
41	1500	10.2	267	20
46	1700	9.4	167	20
47	2000	9.4	166	20

Initial pressure 10 bar(a), 1 dust container

Test number	Dust concentration (g/m³)	Pmax (bar)	dP/dt (bar/s)	ΔP (bar)
37	1000	58.8	188	20
38	1175	60.6	202	20
49	1400	71.0	213	20
48	2000	70.1	128	20
40	1425	67.0	406	35
39	1500	71.7	363	35

Initial pressure 10 bar(a), 2 dust container

Test number	Dust concentration (g/m³)	Pmax (bar)	dP/dt (bar/s)	ΔP (bar)
66	1650	76.0	422	20
71	3000	97.9	442	20
67	3250	102.0	212	20
68	3700	97.4	638	35
69	4000	99.5	890	35
70	4500	99.6	711	35

Initial pressure 15 bar(a), 2 dust container

Test number	Dust concentration (g/m³)	Pmax (bar)	dP/dt (bar/s)	ΔP (bar)
73	1250	94.6	622	30
74	2500	119.3	710	30
75	3250	116.1	589	30
76	3500	121.4	713	30
77	4000	131.0	815	30
78	7500	139.0	1462	30

INERTING TESTS AT ELEVATED INITIAL PRESSURE

Inerting at 5 bar(a)

Test number	Oxygen content (%)	Dust Concentration (g/m³)	Pmax (bar)	dP/dt (bar/s)
81	8	2000	0	0
93	9	2000	0	0
94	9	3000	0	0
95	9	1000	0	0
96	9	2000	0	0
91	10	2000	40.1	84
90	11	2000	42.6	168
88	12	2000	44.3	248
86	13	2000	46.3	266
85	14	2000	47.8	329
84	16	2000	51.3	383

Inerting at 12 bar(a)

Test number	Oxygen content (%)	Dust Concentration (g/m³)	Pmax (bar)	dP/dt (bar/s)
97	9	4000	0	0
98	10	4000	0	0
99	11	4000	0	0
100	12	4000	0	0
106	13	2000	0	0
107	13	1000	0	0
108	13	3000	0	0
109	14	2000	49.3	4.2
110	15	2500	47.5	3.2

Inerting at 18 bar(a)

Test number	Oxygen content (%)	Dust Concentration (g/m³)	Pmax (bar)	dP/dt (bar/s)
111	9	3000	0	0
112	10	2500	0	0
113	11	2500	0	0
114	12	2500	0	0
115	13	2500	0	0
116	14	2500	0	0
118	14	1500	0	0
119	14	3500	0	0
120	14	2500	0	0
121	15	2500	81.3	9

SAFETY-TECHNICAL CHARACTERISTICS OF FOREST RESIDUE, COAL AND STRAW

PART 2. SPONTANEOUS IGNITION TESTS

by

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Submitted by

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Production technology   1

CONTENTS

1   INTRODUCTION   2

2   SELF-IGNITION TESTS   2

    2.1   Treatment of test materials   2
    2.2   Self-ignition hazards   5
    2.3   Theoretical background   6
    2.4   Determination of spontaneous ignition   9
    2.5   Results   10

3   CALCULATORY EXTRAPOLATION AND THE TIME FACTOR   17
    3.1   General   17
    3.2   Thermal conductivity   17
    3.3   Extrapolation   18
    3.4   Time required for spontaneous ignition   20

4   CONCLUSIONS   24

REFERENCES

APPENDICES

1   INTRODUCTION

A common feature of biomasses is their rather heterogeneous physical state. The thermal processes (combustion, gasification, pyrolysis) applied today require almost without exception a homogeneous fuel and hence a fairly exhaustive pretreatment. The pretreatment usually includes drying, crushing, grinding and sieving, and in all these stages the inhomogeneity and dusting of biomasses hamper their easy and safe treatment. Knowledge of safety-technical characteristics of biomasses is of crucial significance for the preparation of safety systems and instructions, and for the assessment of explosion and fire hazards.

The aim of the project is to measure and assess safety factors related to pressurized feeding of different fuels. Self-ignition characteristics of forest residue chips, coal and straw are measured in pressurized conditions. The effect of inertization used for preventing self-ignition during handling is also measured.

During the first year of this two-year project, self-ignition properties of forest residue chips and coal were studied both at normal atmospheric pressure and in pressurized conditions. The effect of different types of inert gas on self-ignition temperatures at different pressures have also been studied. A survey of different possibilities to conduct dust explosion experiments at high initial pressure and temperature has also been completed.

2   SELF-IGNITION TESTS

2.1   Treatment of test materials

The particle size of forest residue was rather coarse and the materials were, therefore, milled by a disc refiner two times to obtain a sufficiently fine particle size for a homogeneous mixture suitable for the tests. The particle size of forest residue chips ,coal and straw are shown in Figure 1. Other characteristics and chemical composition of the fuels are presented in Table 1.

The self-ignition temperature is affected by the volume weight of biomass in practice. As there was no exact value of volume weight in practice available, the volume weight was determined with a laboratory method generally used by machine manufacturers for bulk material when dimensioning equipment if no design bulk density is available. The method has been presented in /1/.

The volume weight measurements were carried out with a 500 cm³ vessel as shown in Figure 2 by filling the vessel to the brim through the funnel, by dropping the vessel to its base with 3 mm amplitude 1 000 ± 50 times and by measuring the change in volume. This operation was repeated so many times that the difference of two consecutive measurements is < 50 cm³. The final loaded volume weight is calculated from this last volume.

Results obtained with this method have been compared with volume weight measurements carried out for peat in a 5.4 m³ bin at the Laboratory of Fuel and Process Technology of VTT in 1986 /2/, which indicated fairly similar results.
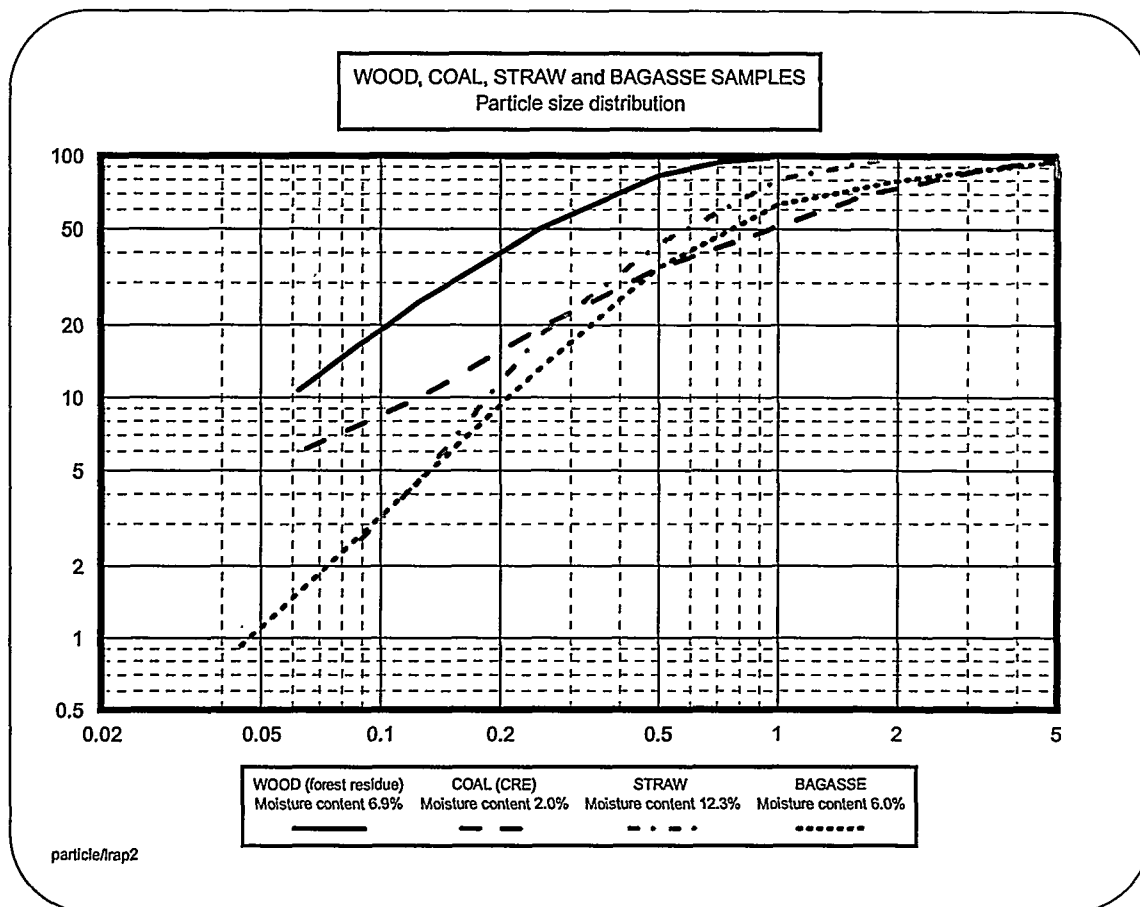

Figure 1. Particle size of forest residue (milled), straw, bagasse and coal used in ignition tests.

Table 1.   *Characteristics of forest residue chips compared with those of some other fuels used in ignition tests.*

|	Forest residue	Straw (dried)	Bagasse	Coal*
Particle size, D50, mm	0.22	0.6	0.8	~0.95
Moisture content, %	6.9	11.6	5.84	3.9
Ash content, % of dry matter	2.6	4.7	15.2	16.2
Volatiles, % of dry matter	78.8	77.7	71.1	31.9
C content, % of dry matter	53.1	47.3	42.4	63.4
H content, % of dry matter	5.9	5.8	5.2	4.0
N content, % of dry matter	0.3	0.6	0.3	1.1
O content (by difference), %	38.1	41.6	36.9	8.5
S content (total)	-		0.03	1.6
Chlorine	-			0.21
*-Proximate and ultimate analysis given by British Coal				
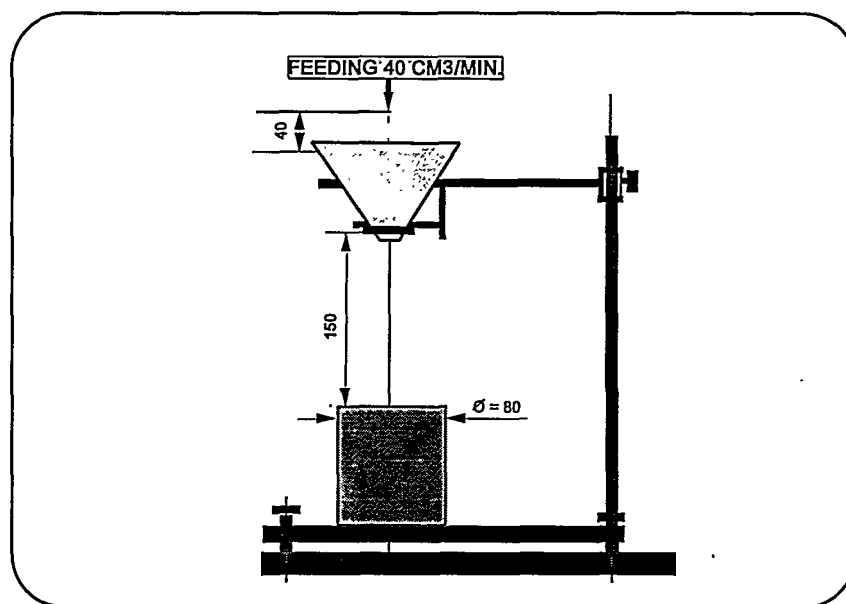
Figure 2. *Measuring equipment of volume weight (FEM).*
(Federation Europeenne de la Manutention,Working Group 4,
Pneumatic Handling,Agenda. 4th October ,1983, Paris) .

Table 2. Results of volume weight measurements for forest residue chips

Fuel	Density kg/m³ (loose)	Density kg/m³ (compacted)
Forest residue / coarse	196.5	238.3
Forest residue / fine	216.8	273.8
Saw dust	253.9	274.1
Straw (<3mm,dried)	67.4	91.3
Bagasse (<4mm)	81.0	105.1
Coal	840.3	910.9

2.2   Self-ignition hazards

In the statistics on dust explosions in coal and peat plants in Germany, the ignition source has often, in more than 20 % of explosions, been self-ignited fuel. The most common ignition sources of dust explosions in coal and peat handling in Germany are presented in Table 3.

Table 3. The proportion of different ignition sources in coal and peat dust explosions /6/ .

Ignition source	% of cases
Self-ignition	20.5
Smouldering	15.4
Hot surface	12.8
Fire	12.8
Mechanical sparks	5.1
Mechanical heating	5.1
Welding (flame. sparks. etc.)	2.6
Electrical tools (cable lamps)	2.6
Unknown. or not given	12.8
Other	10.3

When storing and handling biomass and other fuels, the tendency to spontaneous ignition and the temperature required for ignition should be known. Primarily four factors contribute to spontaneous ignition:
1.   oxidation tendency
2.   ambient temperature
3.   amount and characteristics of the material
4.   shape of the material storage vessel.

Changes in the oxidation tendency of the material also affect its tendency to spontaneous ignition. The ambient temperature and the amount and form of the stored material are of

significance, as heat generation typically occurs in proportion to volume and heat losses occur through the surface. As the volume increases according to the third power and the surface area according to the second one, there is a critical amount of material in which the generated heat is able to escape through the surface relatively quickly to prevent the temperature within the material from reaching the ignition point. The prevailing pressure also affects the tendency to spontaneous ignition via oxidation and heat transfer.

Materials consisting of combustible substances always heat spontaneously to some extent due to exothermic reactions. These materials have no exact self-ignition temperature, but self-ignition is dependent i.a. on the amount of the material. The self-ignition temperature is defined in this case as the temperature, at which the heat amount produced by oxidation per time unit and, on the other hand, the heat efficiency transferring from the outer surfaces of the material to the surroundings and their derivatives with regard to temperature are equal. The temperature dependence of reaction rate is usually very highly unlinear. Consequently, if the temperature exceeds the self-ignition temperature, the heat yield is greater than the heat losses, and as a result the reactions are accelerated further by the temperature rise. The temperature continues to rise until a new stationary state, i.e. combustion temperature, is reached.

2.3   Theoretical background

The theory of spontaneous combustion has been discussed by Bowes /3/ and Beever /4/. It has been found that the critical boundary of conditions between safe and unsafe storage of a material can be indicated by the equation:

$$\ln \frac{\delta_{c} \cdot T_A^2}{r^2} = M - \frac{P}{T_A} \qquad (1)$$

where T_A =   ambient temperature, K
   r =   characteristic dimension (e.g., radius of a cylindric bin)
   δ_c =   Frank Kamenitskii parameter depending on geometries
   M and P =constants of the material.

Equation (1) describes critical conditions - if the temperature is higher than T_A and/or if the size of the storage bin is larger than r, ignition will take place. If the temperature is lower than T_A, or the size smaller than r, the storage bin is safe. The value of the parameter δ_c is available from the literature /4/ and the parameters M and P have to be determined experimentally.

The principle of isothermal test methods is to establish constants M and P in the laboratory so that T_A can be predicted for a given r for a known geometry in the practical case, or vice versa. This is done by finding the critical ambient temperature T_A for the ignition of at least three relatively small samples of material in the laboratory. Equation (1) can be used to extract M and P by linear extrapolation, and when δ_c and r for the practical situation have been substituted into the equation T_A can be deducted.

A number of methods have been suggested for the determination of the temperature of spontaneous ignition. They differ from each other mainly with regard to the used sample amount. Cylindric sample vessels made of steel wire net, with equal diameter and height, are most commonly used. The determination is carried out in a heating chamber as shown in Figure 3 /5/.

For small material amounts it is possible that the long-term combustion temperature is not reached, but the material burns out earlier. To define the self-ignition temperature of the material, it is necessary to know the rate of reactions, and also the heat conductance λ, amount and form of the material. In small material amounts, the heat transfer coefficient α also affects the heat losses in the boundary surface between the material and its surroundings, while in larger amounts, the cooling efficiency is often determined by the heat conductance of the material itself.

In the following the rate of combustion reaction is given as a product of the frequence factor f and exponent expression $e^{-E/RT}$, which is dependent on activation energy E. In particular, the prediction of frequence factor f, or at least its order of magnitude, is very difficult, as it is affected by several parameters (i.a., temperature, particle size, oxygen content, catalysts).

Although a balance prevails between heat flows at self-ignition temperature T_i and, consequently, the temperature distribution in the material is independent of time, it is
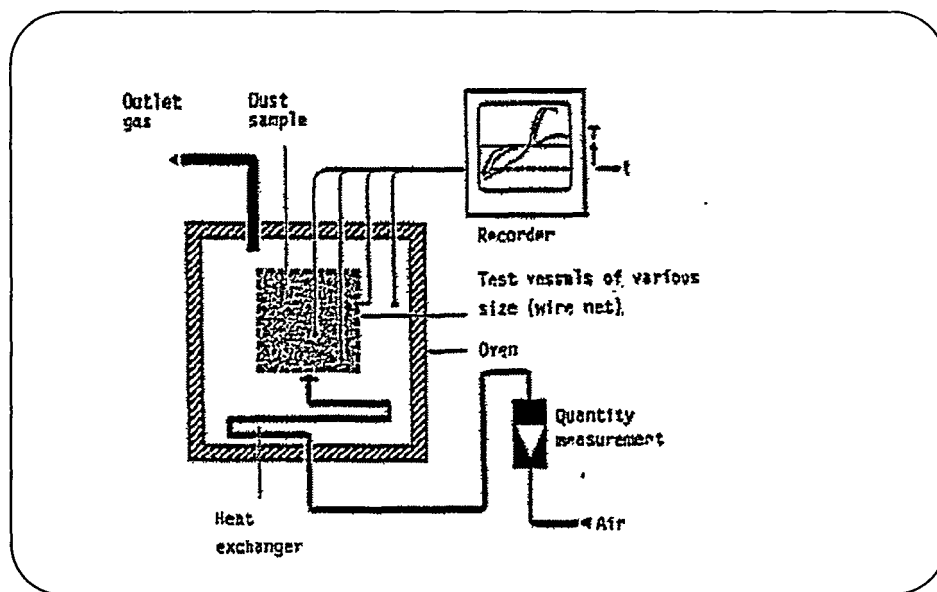

Figure 3. The determination of spontaneous heating in air atmosphere and at normal pressure.

impossible to reach an exact analytical solution of the problem due to the unlinearity of the chemical reaction. Hence, it is usually assumed, for the sake of simplicity, that the internal relative temperature differences of the material amount are small.

In the following, mathematical determination of ignition temperature is discussed /7/. This method has been used in the calculational treatment of tests carried out in this project.

First, a small fuel amount with regard to heat losses is studied. The heat efficiency liberated for a volume unit is:

$$q(r) = Q \bullet \rho \bullet f \bullet e^{-E/RT(r)}$$

Q = reaction temperature/mass unit of fuel
ρ = density of fuel

The thermal effect transferring through the external surface of the material is:

$$Q = \alpha \bullet A \bullet \Delta T$$

A = external surface area
ΔT = T - T_i = temperature difference between the external surface of
the fuel and the surroundings

As a small amount of material is concerned, the fuel is supposed to be at the same temperature

$$T(r) = T$$

The following two conditions are obtained for the determination of self-ignition temperature on the basis that the material is in heat equilibrium and that this equilibrium remains although the temperature of the material changes differentially:

$$VQ\rho fe^{-E/RT} = \alpha A \Delta T_i$$

$$VQ\rho fe^{-E/RT} \bullet E/RT^2 = \alpha A$$

The value of self-ignition (described by the difference ΔT_i) at the self-ignition temperature is obtained by solving the above equation pair.

On this basis, a typical value of forest residue chips could be, for example: T=473.15 K (~200C) and if E=100 kJ/mol (which is equal to E/R value 12 000 K), giving

$$\Delta T_i = 18,5K$$

According to this self-ignition occurs, if the temperature of the fuel concerned is 18.5 K higher than that of the surroundings.
Correspondingly, for a fuel amount with self-ignition temperature T_i= 293 K (~20 C) the temperature rise revealing ignition would be only 7 K provided that the activation energy of the reaction at this temperature is equal to that given above.

2.4   Determination of spontaneous ignition

Spontaneous ignition is usually studied on at least three samples of different volumes to be able to extrapolate the results for larger amounts. The samples are usually small, or else the time required by the tests would be too long. In small samples, the temperature changes quickly and hence the determinations can be carried out rapidly, although the accuracy is poor. The sample can be of any shape; however, cylindrical ones (according to bin shape) are most often used.

The following method is used at the laboratory of VTT Energy for determining spontaneous ignition at an elevated pressure. The principle of the equipment is shown in Figure 4.

A cylindrical fuel sample is placed in a metal mesh vessel and then into an autoclave. The determination is carried out by raising the pressure in the autoclave to the desired level (1 , 25 bar) by introducing simultaneously the desired gas atmosphere in the autoclave. Prior to feed, the temperature of the gas is raised to that of the autoclave to secure a steady temperature around the sample. The ambient temperature is raised stepwise at 10° steps (max 220 °C) with a heat coil located on the inner walls of the autoclave. The gaseous atmosphere is dynamic, as the gas flows slowly through the autoclave and the composition of the gaseous atmosphere is nearly constant. The sample is kept at each temperature stage a sufficiently long time (usually from one to several hours) to monitor whether the ambient temperature is sufficiently high for spontaneous ignition. The temperatures of the midpoint, and of one end of the sample as well as the temperature of the gas, are recorded. The temperature of the gas volume near the sample at the moment of spontaneous ignition is given as the result of the determination.
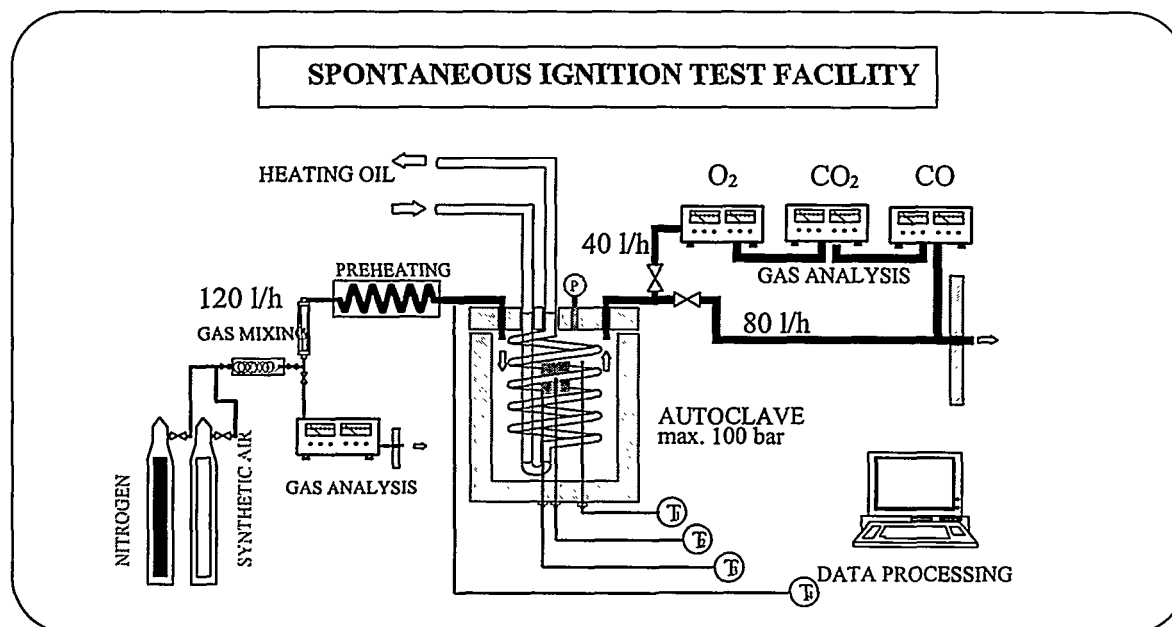

Figure 4.   Schematic of test equipment for spontaneous ignition in pressurized and inertized atmosphere.

The composition of the inlet and outlet gas is measured with continuously operating gas analyzers to control the stability of the gaseous atmosphere and also to record the moment of spontaneous ignition on the basis of change in the composition of the outlet gas. Nitrogen is typically used as an inert gas to dilute the oxygen concentration below ignition limits except for the use of special gases, such as flue gas for inerting. The temperatures and gas analyses are recorded automatically by a data logger. The sample is changed rather often, depending on the temperature level, irrespective of whether it is ignited or not. The ignition characteristics can change, if the same sample is kept at the elevated temperature too long.

If the fuel is conveyed hot to the store (lock hopper), for example, direct from the drying process, it has an increased tendency to self-ignition already at a lower temperature than usually. This tendency is determined by calculating the heat conductance of the fuel at normal operating temperature and by extrapolating these values for the full-scale storage bins. In addition to the heat transfer factor mentioned above, the heat capacity of the fuel also affects the time required for self-ignition.

2.5   Results

The ignition temperatures were determined both using a normal oxygen content of air and different inert gases with a reduced oxygen content. Three kinds of flue gases were used as inert gases, instead of the normal nitrogen dilution applied earlier.

   1) Dry flue gas from gas fired boiler (O_2 = 3 %)
   2) Dry flue gas from gas turbine (O_2 = 14 %)
   3) Dry combustion flue gas (British coal) in self-ignition tests with coal (O_2=5%)

The accurate content of these gases is presented in Appendix 1.

For comparison, results determined with nitrogen-diluted oxygen contents are also presented.

The tests were carried out both at atmospheric and elevated pressures with samples of about 50, 100 and 400 cm^3. The net-structured sample baskets were cylindric, the height being equal to the diameter. Figures 5 and 6 show examples of output obtained in a test carried out with bagasse at 1 bar and with coal at 25 bar. The essential results are shown in Tables 4-5 and in Figures 7 - 11. These results also include an extrapolation for two bigger bin volumes /diameters (D=3m and D=2m) . In Table 6, values obtained for other fuels in some earlier experiments and new results are presented. The accuracy of the measured self-ignition temperature was about 5 °C in these experiments.
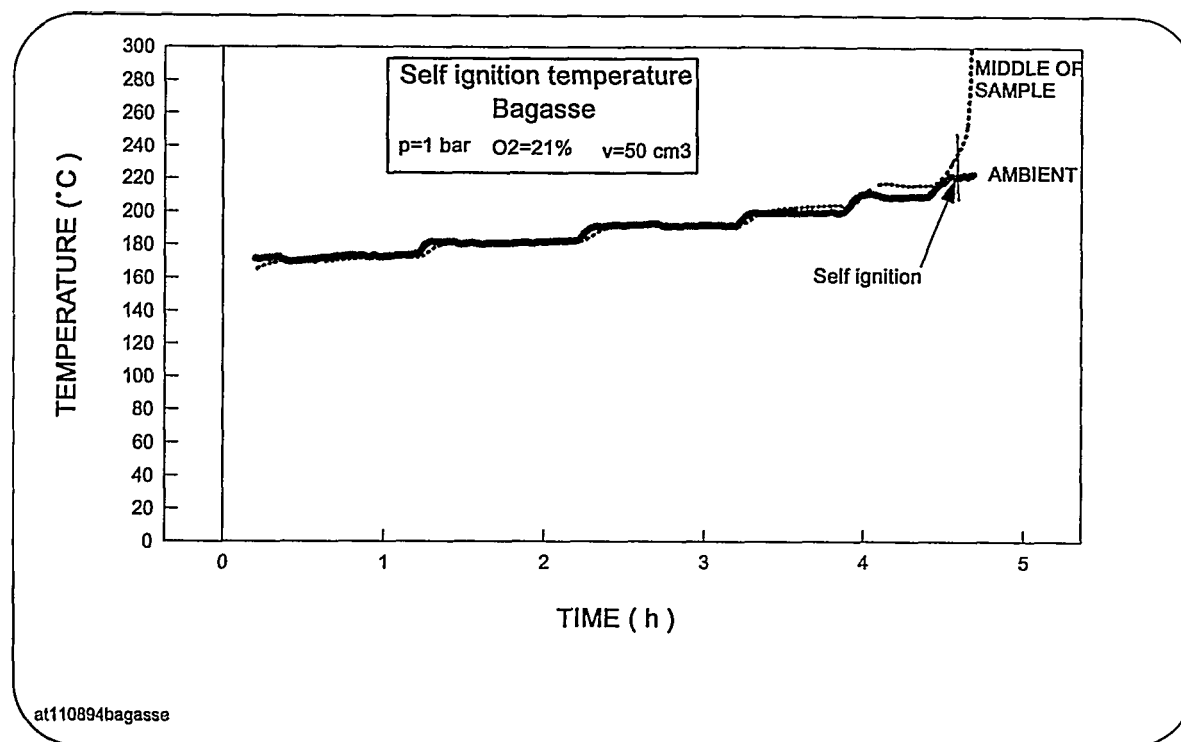
*Figure 5.Development of temperatures in a test with spontaneous ignition of bagasse when
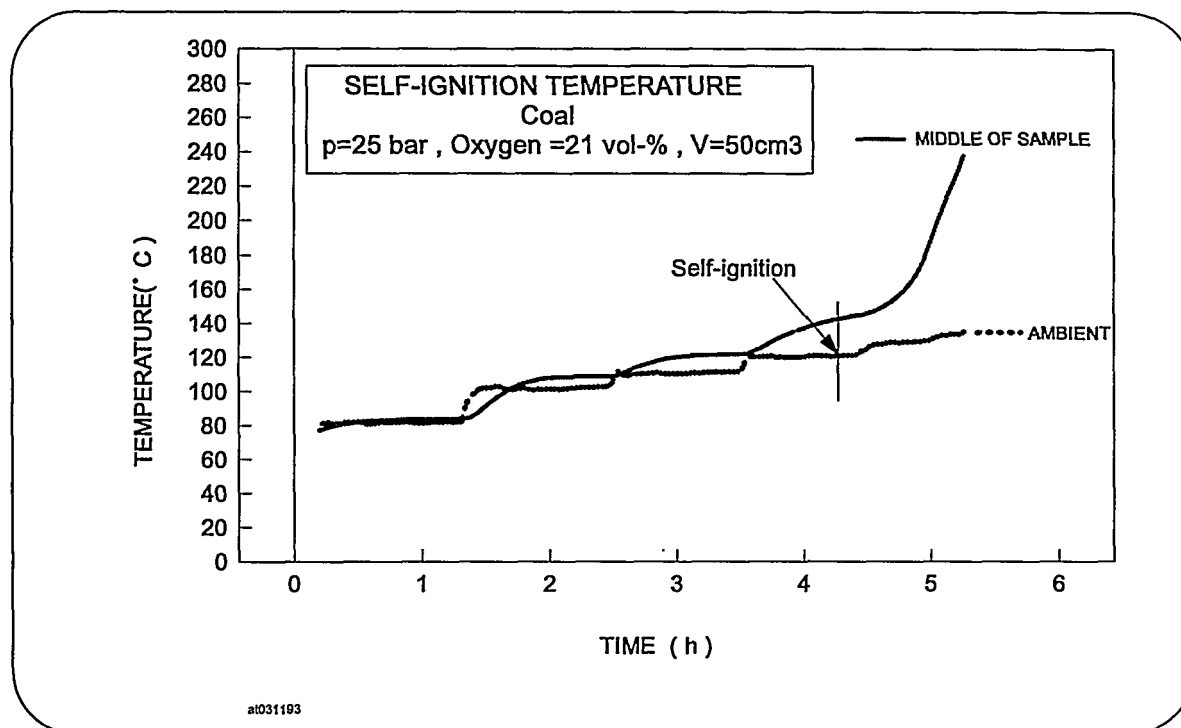the sample ignited .*

*Figure 6.Development of temperatures in a test with spontaneous ignition of coal when
the sample ignited (p = 25 bar).*

Table 4. Ignition temperatures for different biomasses

Ignition(°C) V = 6.3 m³ D = 2 m (Calculated)	Ignition(°C) V = 21 m³ D=3 m Calculated)	Fuel	Pressure bar	Sample size cm³	Ignition °C	(O₂)- %
123.5	117.4	Forest residue	1	50	194.2	air 21
		Forest residue	1	100	188.1	air 21
		Forest residue	1	400	179.8	air 21
125.8	119.3	Forest residue	1	50	197.6	14
		Forest residue	1	100	192.2	14
		Forest residue	1	400	182.9	14
113.5	109.2	Forest residue	25	50	162	air 21
		Forest residue	25	100	158	air 21
		Forest residue	25	400	152.5	air 21
116.3	111.6	Forest residue	25	50	169	14
		Forest residue	25	100	162.5	14
		Forest residue	25	400	159.8	14
153.7	150.9	Forest residue	25	50	182.4	nitrogen 2.5
		Forest residue	25	100	179.7	nitrogen 2.5
		Forest residue	25	400	177.1	nitrogen 2.5
139.1	134.8	Forest residue	25	50	185.4	3
		Forest residue	25	100	182.7	3
		Forest residue	25	400	176.5	3
148.5	141.9	Forest residue	1	50	224.0	3
		Forest residue	1	100	219.0	3
		Forest residue	1	400	208.7	3
127.2	121.4	Straw	1	50	193.6	21
		Straw	1	100	189.4	21
		Straw	1	400	180.3	21
117.3	111.8	Straw	25	50	180.5	21
		Straw	25	100	176	21
		Straw	25	400	167.8	21
136.8	129.1	Straw	1	50	230.8	3
		Straw	1	100	222	3
		Straw	1	400	211	3
129.7	124.1	Straw	25	50	193.6	3
		Straw	25	100	189.1	3
		Straw	25	400	180.8	3
123.7	115.6	Bagasse	1	50	222.3	21
		Bagasse	1	100	220.3	21
		Bagasse	1	400	203	21

Table 5. Ignition temperatures for coals .

Ignition($°$C) $V = 6.3\ m^3$ $D = 2\ m$ *(Calculated)*	Ignition($°$C) $V = 21\ m^3$ $D=3m$ *(Calculated)*	Fuel	Pressure bar	Sample size cm^3	Ignition $°$C	(O_2)-%
49.8	40.6	Coal(Bc)	1	50	181.9	5
		Coal (Bc)	1	100	170.1	5
		Coal (Bc)	1	400	150.7	5
45.1	37.7	Coal (Bc)	25	50	141.7	5
		Coal (Bc)	25	100	133.0	5
		Coal (Bc)	25	400	120.3	5
42.0	33.9	Coal (Bc)	1	50	153.0	21
		Coal (Bc)	1	100	140.8	21
		Coal (Bc)	1	400	127.8	21
37.1	30.6	Coal (Bc)	25	50	120.0	21
		Coal (Bc)	25	100	110.9	21
		Coal (Bc)	25	400	102.3	21

Table 6. Ignition temperatures at various pressures for different fuels ($O_2 = 21$ %).

Fuel	Sample (cm3)	Ignition($°$C) p=1bar	Ignition($°$C) p=10bar	Ignition($°$C) p=20bar
Saw dust	50 100 400	183	168 164	.
Peat (steam dried)	50 100 400	158	151 145 139	145 136 132
Bark (steam dried)	50 100 400		159 154 146	146 142 135
Lignite (dried)	50 100 400	154	146 131 116	128 123 112

Figure 7 shows self-ignition temperatures for forest residue at various initial pressures and at 4 % , 14% and 21% oxygen content for a 400 cm³ sample (= the largest sample size used in the tests). It should be borne in mind that O_2 = 14 % points were obtained with turbine inert gas, in which part of nitrogen had been replaced by CO_2 (7 %). However, these did not differ from the results of self-ignition tests with pure nitrogen as inert gas.

In Figure 8, a calculatory extrapolation to bin size 21 m³ has been made on the basis of the results obtained for the measured three sample sizes (50 cm³, 100 cm³ and 400 cm³) . The calculated self-ignition temperature is shown as a function of oxygen content . The effect of pressure as a factor of reducing the self-ignition temperature is in this case a little smaller than the effect measured for the 400 cm³ sample.

In Figure 9 the self-ignition temperatures of a small coal sample as a function of oxygen content are shown. In Figure 10, the calculatory extrapolated self-ignition temperatures for the 21 m³ bin as a function of oxygen content are presented.

The extrapolated self-ignition temperatures for the fuels (21 m³ bin) with different oxygen contents and at different pressures are presented in Figure 11. As can be seen in figure 11 , the coal seems ignite in large (extrapolated) volumes at significantly lower temperatures than the biomasses do , although the self-ignition temperatures of small samples in separate tests were not especially low.
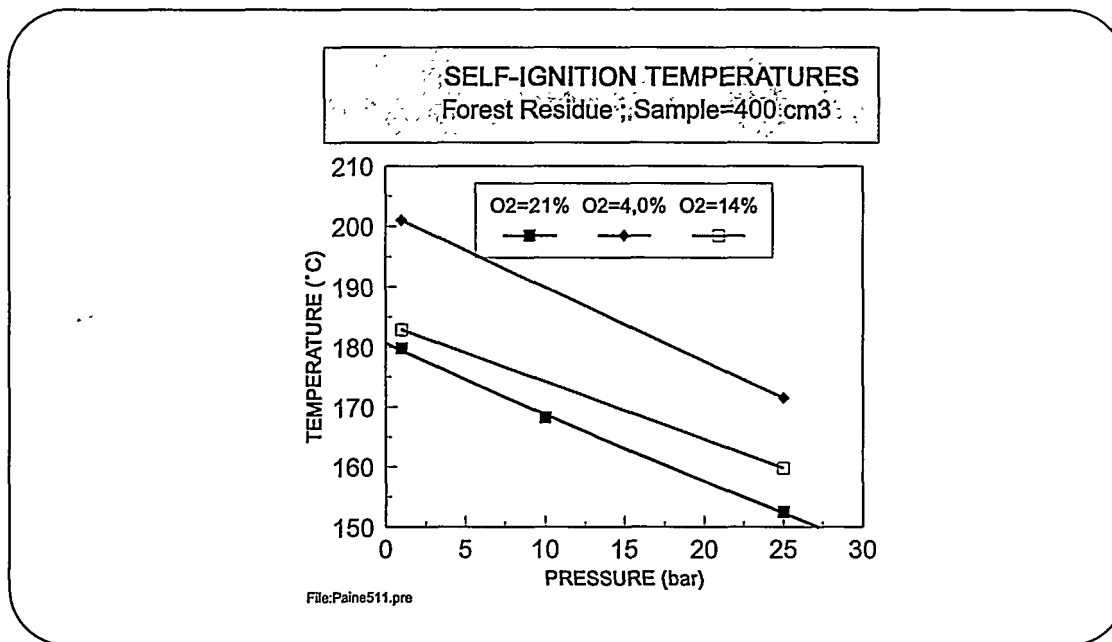
Figure 7. Self-ignition as a function of pressure with air, nitrogen-inertized gas (O_2 = 4 %) and with dry flue gas from turbine (O_2 = 14 %).
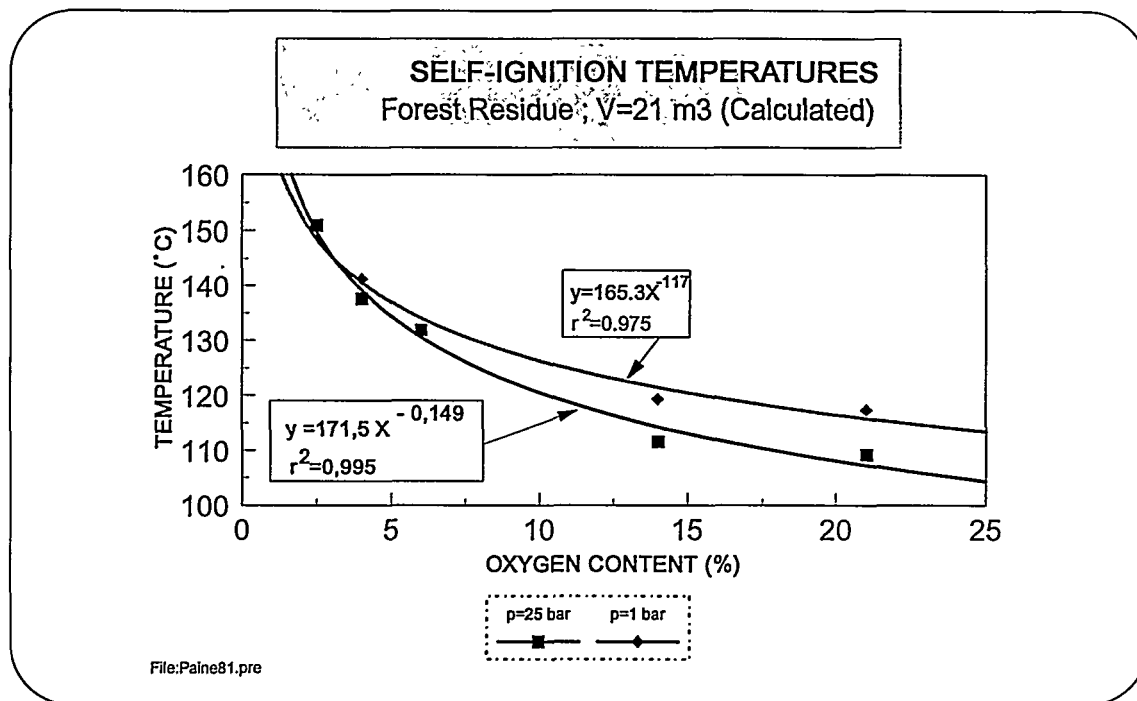
Figure 8. Self-ignition temperature extrapolated to the bin size (21 m³) at different pressures and with different oxygen contents (O₂ = 14 % points inertized with turbine gas).

Figure 9. Self-ignition temperatures of coal as a function of oxygen content and pressure (sample 400 cm³).

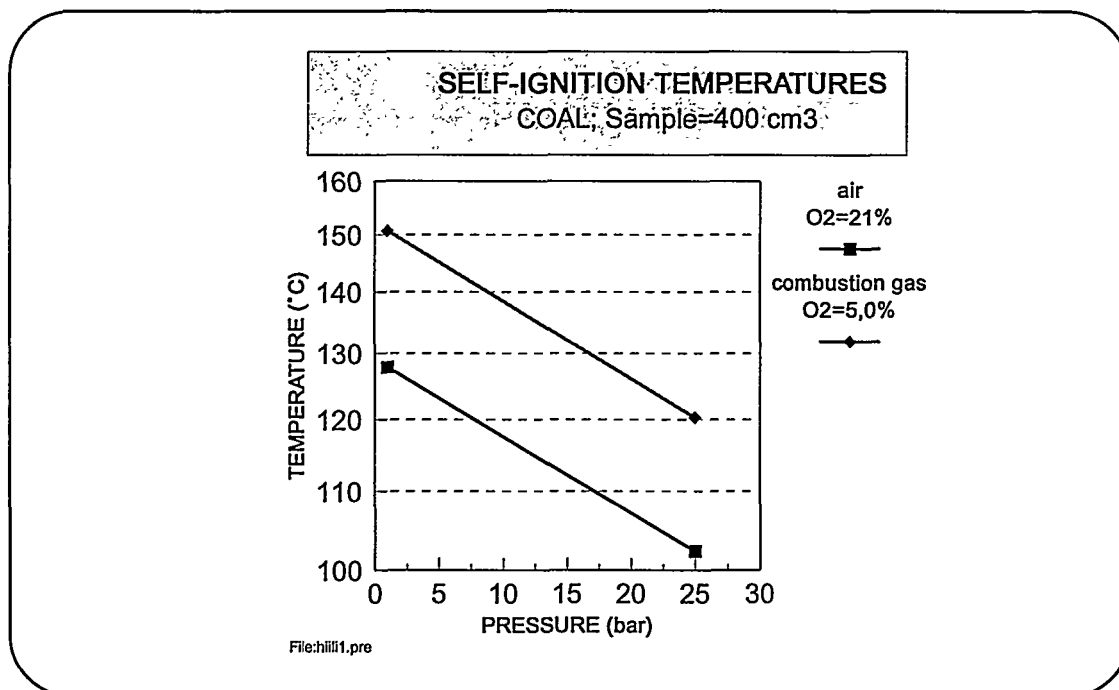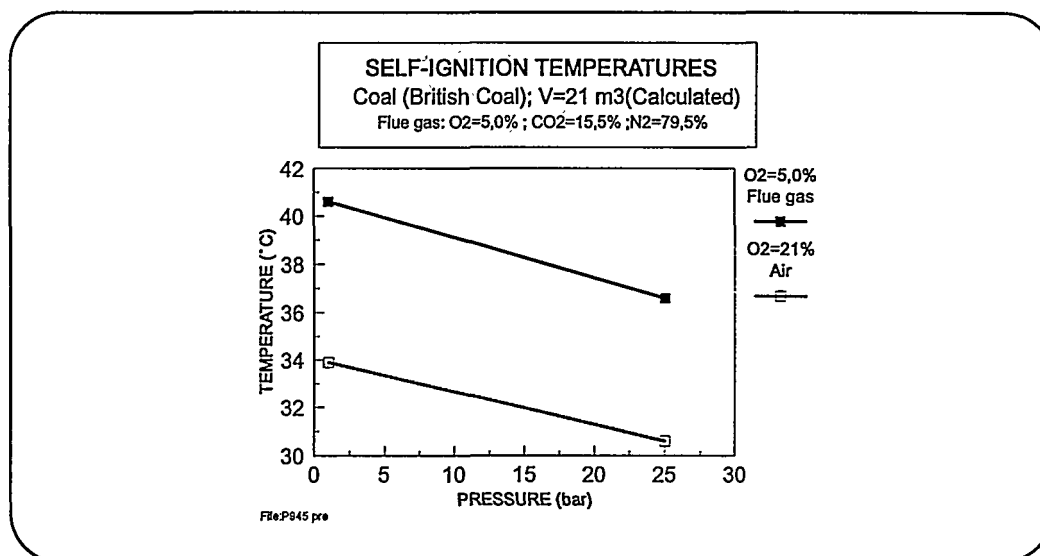*Figure 10. Self-ignition temperature of coal extrapolated to bin size (21m³) at different pressures and with different inertization gases.*
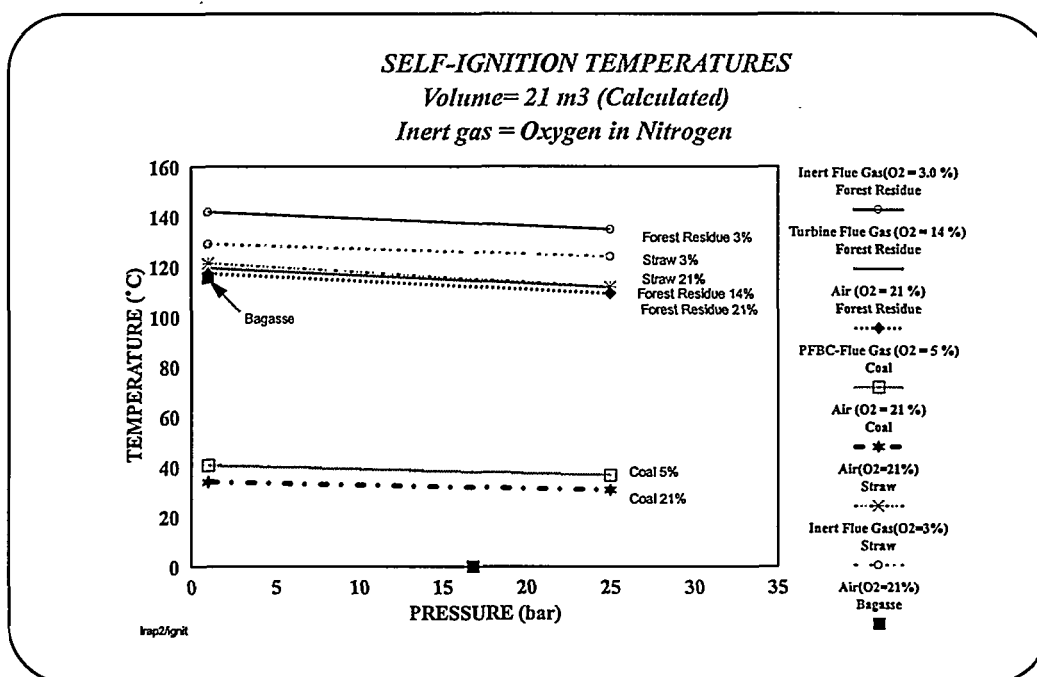

Figure 11. Self-ignition temperatures (V = 21 m³) of different fuels with different oxygen contents and at different pressures.

3. CALCULATORY EXTRAPOLATION AND THE TIME FACTOR

3.1 General

Spontaneous ignition is determined according to the test method so that the self-ignition temperature is the ambient temperature, by the effect of which the middle of the sample is ignited. This procedure and the required temperature difference, at which spontaneous ignition is mathematically possible, is discussed in further detail in the pages 6 - 8.

3.2 Thermal conductivity

It is necessary to know the thermal conductivity of the fuel to be able to determine, at least approximately, the time factor involved in spontaneous ignition. The thermal conductivity should be determined in conditions of spontaneous ignition. In particular, factors such as the density and initial temperature of the fuel in the storage bin should be known when determining the time required for spontaneous ignition. The time of ignition is also affected by the temperature of the fuel during the feed into the bin (for example, the temperature is clearly higher than the ambient temperature due to drying). The thermal conductivity values for different fuels determined at VTT are presented in Table 7

Table 7. The thermal conductivity of fuels .

Fuel	Measuring depth (d) mm	Mean temperature (Tm) °C	Temperature gradient (T/d) K/m	Density of heat flow (q) W/m²	Thermal conductivity l_{10} [W/(m*K)]	Moisture content (%)
Wood	50	65.4	1 855	14.8	0.07	6.9
Wood	50	30.7	447	3.3	0.07	6.9
Straw	50	9.7	332	13.8	0.042	12.3
Coal	50.5	10.2	378	41.3	0.11	2

Thermal conductivities of fuels are shown in Figure 12 . As the measuring temperature of thermal conductivity also affects the results , Figure 12 also includes the mean temperatures in the measurements.
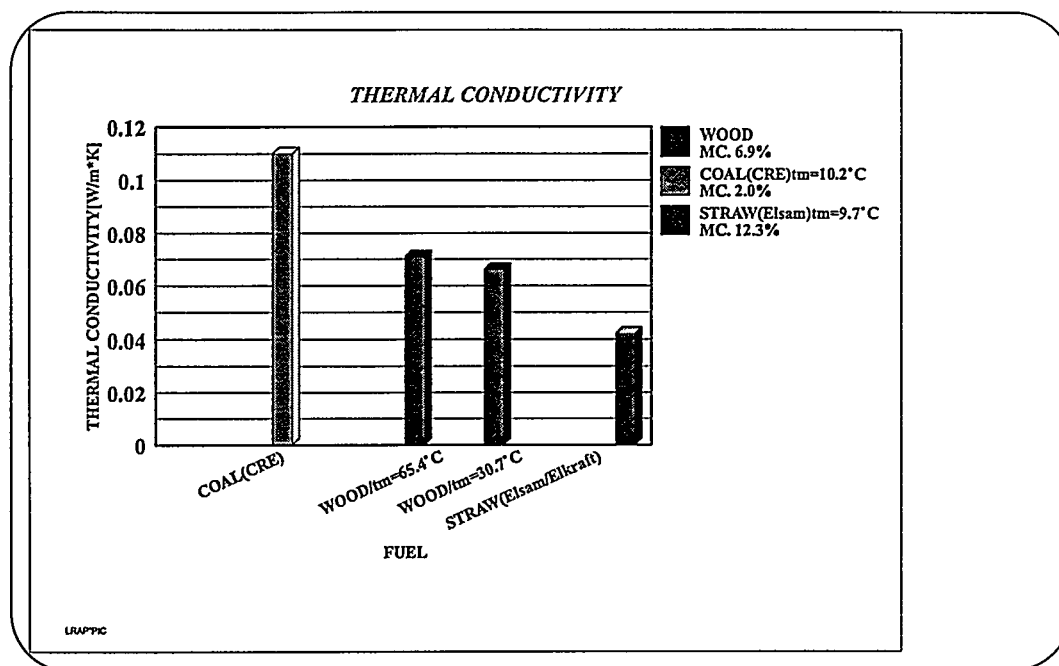
Figure 12. Thermal conductivity of different fuels .

3.3   Extrapolation

Calculation methods related to extrapolation and to the determination of the time factor are presented in the following section. The example is for a forest residue bin of 21 m³ in air atmosphere (p=25 bar). The self-ignition temperature and parameters of spontaneous ignition dependent on the temperature of the environment and the fuel in one separate case have been calculated. It should be borne in mind that the final result is changed if even one value of the separate parameters is changed. The gas atmosphere used in the tests consisted of synthetic air, O_2=21%. In Figure 13 has been presented the calculation of extrapolated self-ignition value obtained from the treatment of the results and the determination of constants (M) and (P).

The self-ignition values obtained are then verified by recalculating the size of ignition values calculated from the hypothetic value of activation energy, using the new value of activation energy. This value was obtained from the treatment of the results when calculating the size of the minimum temperature difference (Figure 14). This is repeated until the accuracy of the activation energy values are equal to that of the test results.

$$P = E/R \ [K]$$

P = the coefficient of formula (1) obtained from the calculations
E = activation energy
R = general gas constant

TOL := 0.0001

$\delta c := 2.21$

$i := 0..2$

$$T := \begin{pmatrix} 273.15 + 162 \\ 273.15 + 158 \\ 273.15 + 152.5 \end{pmatrix} \qquad r := \begin{pmatrix} 0.019965 \\ 0.02516 \\ 0.03994 \end{pmatrix}$$

$$y_i := \ln\left[\frac{\delta c \cdot (T_i)^2}{(r_i)^2}\right]$$

$$\left(\frac{0.013}{\frac{2}{3.14}}\right)^{\frac{1}{3}} = 0.127$$

$$Ta_i := \frac{1}{T_i}$$

Coefficient := slope(Ta, y)

Constant := intercep(Ta, y)

Correl := corr(Ta, y)

Coefficient = $-2.815 \cdot 10^4$

Constant = 85.497

$$yr_i := Coefficient(Ta_i) + Constant$$

Correl = -0.996

TEMPERATURES
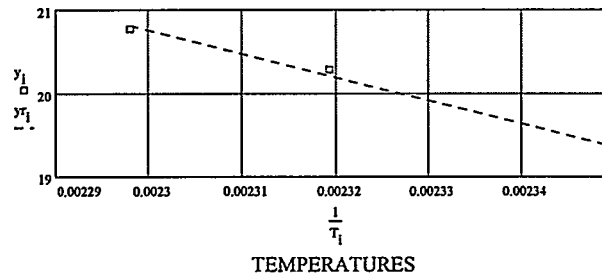
TA := 373   P := |Coefficient| r := 1.5

                                              M := Constant

Given

$$\ln\left(\frac{\delta c \cdot TA^2}{r^2}\right) = M - \frac{P}{TA} \qquad (1)$$

                                              r = 1.5

                                              M = 85.497

                                              P = $2.815 \cdot 10^4$

X := Find(TA)

X = 382.302

                                              t := X - 273.15

                                              t = 109.152

$$\ln\left(\frac{\delta c \cdot X^2}{r^2}\right) = 11.874 \qquad\qquad M - \frac{P}{X} = 11.874$$

Figure 13. Equation (1) used to extract constants (M) and (P).

$$i := 420..440 \qquad T\,(K)$$

$$x_i := \left(\frac{1}{28150}\right)\cdot i^2 \qquad E/R = 28150\ K \qquad \text{Temp.diff.}_{min.}\,(°C)$$

$$y_i := i - 273 \qquad t\,(°C)$$

Figure 14. Calculation of the minimum temperature differences. (Results are presented in table 8)

The value E/R = 28150 K calculated according to (1) is the coefficient obtained for forest residue in the case presented above. The hypothetic value E/R = 12 000 K was used for the determination of the temperature differences required. The calculations can be verified on the basis of these new temperature differences.

Table 8. Minimum temperature differences of spontaneous ignition for forest residue
(p = 25 bar ; O_2 = 21 %, E/R = 28150 K and E/R = 12000 K).

E/R = 28150 K

T (K) i	Temp.diff.$_{min.}$ (°C) x_i	t (°C) y_i
420	6.266	147
421	6.296	148
422	6.326	149
423	6.356	150
424	6.386	151
425	6.417	152
426	6.447	153
427	6.477	154
428	6.507	155
429	6.538	156
430	6.568	157
431	6.599	158
432	6.63	159
433	6.66	160
434	6.691	161
435	6.722	162
436	6.753	163
437	6.784	164
438	6.815	165
439	6.846	166
440	6.877	167

E/R = 12000 K

T (K) i	Temp.diff.$_{min.}$ (°C) x_i	t (°C) y_i
420	14.7	147
421	14.77	148
422	14.84	149
423	14.911	150
424	14.981	151
425	15.052	152
426	15.123	153
427	15.194	154
428	15.265	155
429	15.337	156
430	15.408	157
431	15.48	158
432	15.552	159
433	15.624	160
434	15.696	161
435	15.769	162
436	15.841	163
437	15.914	164
438	15.987	165
439	16.06	166
440	16.133	167

3.4 Time required for spontaneous ignition

The estimated time needed for ignition, so-called induction time, is determined next. The critical radius (r) of hot fuel store can be calculated, if the ambient temperature of the store is

known. Then it is possible to determine the maximum size of the store, in which spontaneous ignition does not occur. In larger stores spontaneous ignition will occur, and consequently, the only way of preventing ignition is to shorten the storage time so much that spontaneous ignition is impossible.

In Figure 19 has been calculated the ignition time for the critical bin size at the corresponding temperatures. The ignition time has been determined in two different ways:

1) For cold fuel in a bin, the ambient temperature of which is the same as the critical temperature.
2) For hot fuel in a bin, the temperature of the fuel is the critical temperature, the ambient temperature being 25 °C.

The effect of the initial temperature of the material on the maximum dimensions of the storage bin is calculated by determining firstly parameter (δ_p) from Figure 16 , when the value of θ_0 (no dimension) is first calculated on the basis of formula (3) from Figure 15. The value of δ_p is affected by the initial temperature of the material and by the ambient temperature.

Ti = initial temperature of the material
Ty = ambient temperature of the material

$$P = 2.815 \cdot 10^4$$

$$Ti := 109.2 + 273.15$$
$$Ti = 382.35$$

$$Ty := 25 + 273.15$$
$$Ty = 298.15$$

$$\left[\frac{P}{(Ti)^2}\right] \cdot (Ty - Ti) = -16.211 = \theta_0 \quad (3)$$

$$\delta p := 25.0$$

Figure 15. The calculation of θ_0 (no dimension)

For example, using the temperature values of forest residue, the value of δ_p for a spherical bin is 25 according to Figure 16 (values can be used for a cylinder as approximate values).
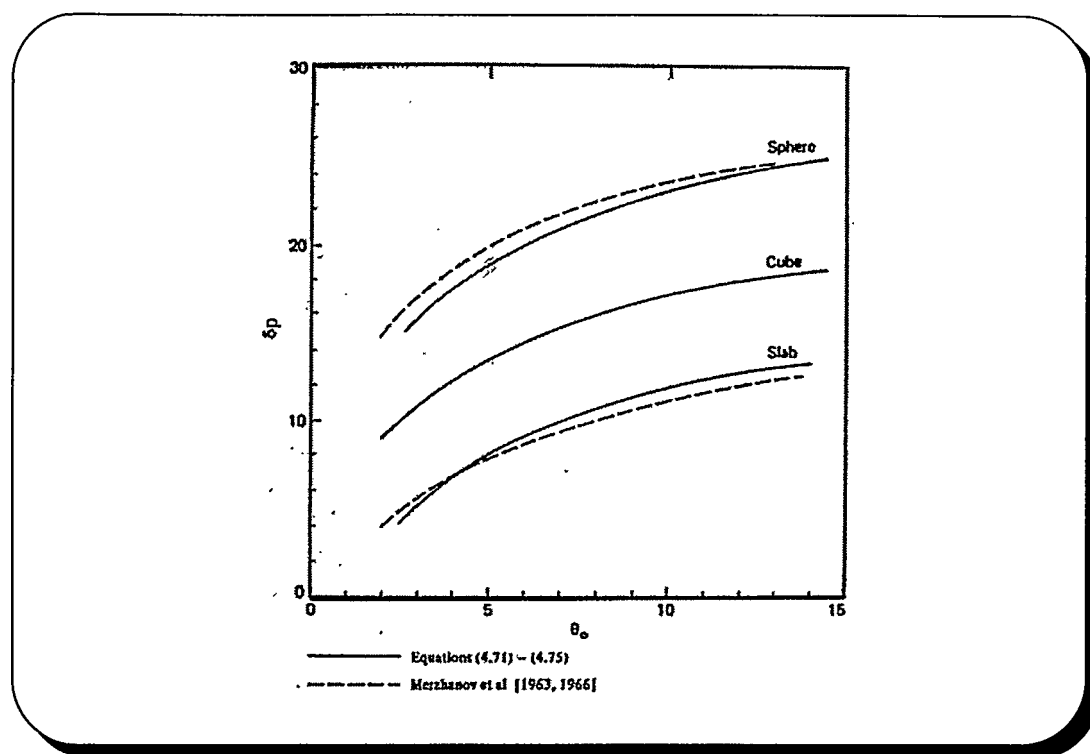
Figure 16 . Determination of theta-value (δ_p) /3/

Given

$$r := 1.5$$

$$P = 2.815 \cdot 10^4$$

$$M = 85.497$$

$$\delta c = 2.21$$

$$Ti = 382.35$$

$$\ln\left(\frac{\delta c \cdot Ti^2}{r^2}\right) = M - \frac{P}{Ti} \quad (2)$$

$$Z := \text{Find}(r)$$

$$r := \sqrt{\frac{\delta c \cdot Ti^2}{e^{\left(M - \frac{P}{Ti}\right)}}}$$

$$Z = 1.493261 \quad = \text{Critical radius of store (m)} \quad r = 1.493261$$

Figure 17. The calculation of critical storage size.

The ignition time is calculated based on the fact that the heat transferring from the surroundings to the middle of the fuel (the lowest ignition temperature is there) requires a certain time. The calculation of the critical radius has presented in Figure 17. The tests have shown that the heat produced by self-oxidation of the fuel at a certain temperature level increases as high that the heat cannot trasfer away at the same rate, and as a consequence, the temperature continues to rise in the middle of the fuel storage and simultaneously also accelerates the oxidation rate. Spontaneous ignition follows after some time.

$$Z = 1.493$$

$$\delta p = 25$$

$$I := 1$$

$\lambda := 0.071$	$\lambda = 0.071$	(W/m K)	Thermal conductivity
$\rho := 273.8$	$\rho = 273.8$	(kg/m^3)	Bulk density (compacted)
$c := 1.36$	$c = 1.36$	(kJ/kg K)	Heat capacity

$$I := \left(\frac{1}{\delta p}\right) \cdot \rho \cdot c \cdot \frac{Z^2}{\lambda} \cdot \frac{1000}{3600 \cdot 24} \quad (4)$$

$$I = 5.414 \quad = \text{Time (days)}$$

Figure 18. The calculation of self-ignition time.

The dependence of self-ignition time on the size of the fuel store and on the storage temperature of the fuel is shown in Figure 19.

Self-ignition time
Forest residue
p=25 bar,O2=21%

Legend:
- Ign.temperature
- Time (days)
- Time(d)Hot fuel

X-axis: Bin diameter (m)
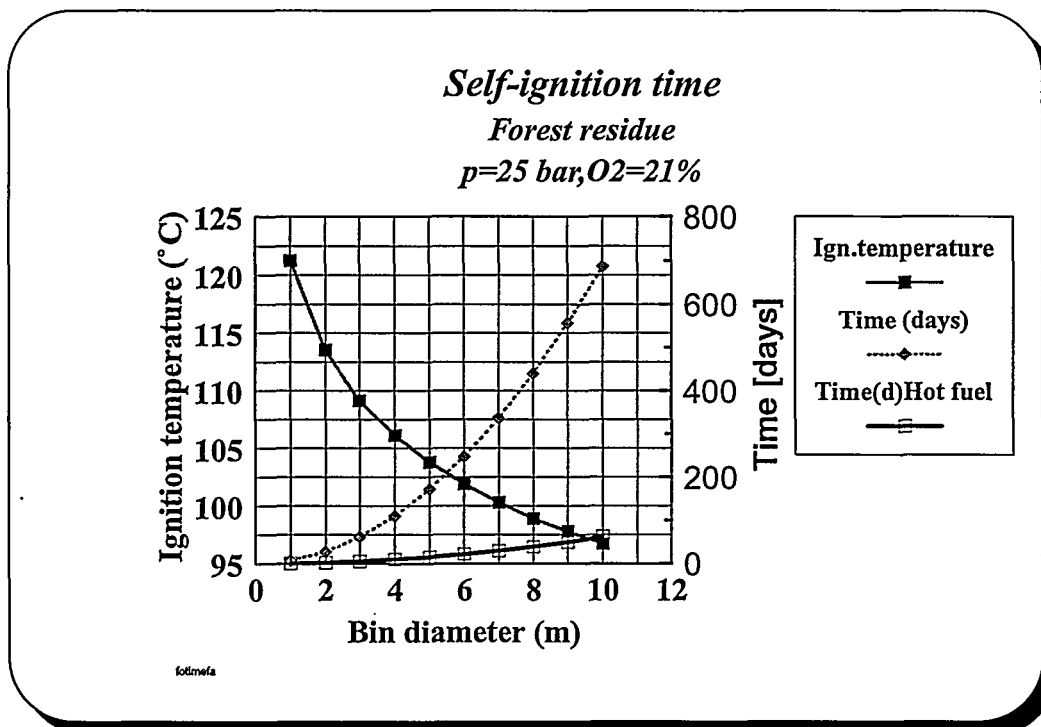Left Y-axis: Ignition temperature (°C)
Right Y-axis: Time [days]

Figure 19 . Self-ignition time as a function of hopper diameter and a critical bin size of hot fuel .

4 CONCLUSIONS

Small samples ignite quickly at elevated pressure (10 and 25 bar), and also at low oxygen contents (usually within 2 - 4 hours), while spontaneous ignition of larger samples may take several days. The reduction of the oxygen content can result in an increase in the ignition temperature. This effect seems to occur at low oxygen levels. The increase of pressure from 1 to 25 bar resulted in lower spontaneous ignition temperatures. Straw and bagasse seemed to ignite approximately in the same temperature area as forest residue . It should be borne in mind that in practice with large amounts of materials, spontaneous ignition temperatures may be much lower than these test values, and differences between materials are quite significant. The coal seemed to ignite in large (extrapolated) volumes at significantly lower temperatures than the biomasses do, although the self-ignition temperatures of small samples in separate tests were not especially low. However, as the volume increases, the self-ignition temperatures of coals are reduced to much lower values than those of the biomasses. In the coal tests, inertization also seemed to contribute much lesser to the rise of self-ignition temperature than in the biomass tests. Due to compactness the actual oxygen content in the core of the sample may be low due to poor diffusion of gases into the sample.

Correspondingly, spontaneous ignition is also possible, when the temperature inside the store rises without external heat transfer, for example, due to the high activation energy and oxidation susceptibility of the fuel. This kind of spontaneous ignition is probable, if the fuel is stored before it has been properly cooled or otherwise lost its susceptibility to oxidation, for example, in small intermediate stores or during pretreatment (crushing and/or sieving).Spontaneous ignition can be prevented in such cases by monitoring the temperature in the middle of the fuel store and, as soon as the temperature approaches the self-ignition temperature extrapolated for the store, by taking preventive measures, for example, reducing, dividing or compacting the store to prevent oxygen diffusion. As soon as the amount of oxygen inside the store is reduced the self-ignition temperature increases.

Storage of the fuel as hot, for example, after drying, shortens the time required for ignition significantly. The self-ignition temperature and the ignition time is also highly dependent on the resistance to heat transfer between the bin and its environment, and on possible heat insulation or heating of the bin.

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The contents of different flue gases.   APPENDIX 1

SELF-IGNITION TESTS
INERT GAS MIXTURES
1993-1994

- *DRY FLUE GAS FROM GAS TURBINE (GT)*
- *COMPOSITION:*
    - *OXYGEN (O2)=14 %*
    - *CARBONDIOXIDE(CO2)=7 %*
    - *STEAM (H2O)= 0 %*
    - *NITROGEN (N2)=79 %*

SELF-IGNITION TESTS
INERT GAS MIXTURES
1993-1994

- *DRY FLUE GAS FROM GAS FIRED BOILER*
- *COMPOSITION:*
    - *OXYGEN (O2)=3 %*
    - *CARBON DIOXIDE(CO2)=19%*
    - *STEAM (H2O)= 0 %*
    - *NITROGEN (N2)=78 %*

SELF-IGNITION TESTS
INERT GAS MIXTURES
1993-1994

- *DRY COMBUSTION FLUE GAS (British Coal)*
- *COMPOSITION:*
    - *OXYGEN (O2)=5 %*
    - *CARBON DIOXIDE(CO2)=15.5%*
    - *STEAM (H2O)= 0 %*
    - *NITROGEN (N2)=79.5 %*

SAFETY-TECHNICAL CHARACTERISTICS OF FOREST RESIDUE, COAL AND STRAW

PART 3. FLOWABILITY TESTS

by

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CONTENTS

1. DESIGN OF TEST BINS ON THE BASIS OF SHEAR TESTS

1.1 Flow properties

The flow technical characteristics of mass materials should be determined so that they are equal to the real loads and conditions prevailing in handling equipment. When determining handling-technical characteristics for fuels the shear test method should be used for mass materials. On the basis of the characteristics obtained with this method, the handling equipment can be dimensioned using a method based on the flow theory for mass materials developed by Jenike (1962) /1/. The Jenike Shear Test Cell is the most well-known measuring equipment, in which the shear is carried out with a linear movement. Shear stress measurements had earlier been carried out at VTT in particular with peat and other biomasses by testing shear test cells of different type and working principles /2/. On the basis of these tests the Walker Annular Shear Cell of (Figures 1&2) was chosen. Unlimited shear length and simple reliable operation were considered as its advantages.

The following characteristics were determined in the shear tests:
- major consolidating pressure, σ_1
- unconfined yield strength, f_c
- internal friction, ϕ
- internal effective friction, δ
- cohesion, c
- N_{FF} value, inverse value of the derivative of linearized flow function, describing the flow of fuel. If the value is > 10, the fuel is considered free-flowing.

A	coal sample
B	annular cell
C	annular shoe
D	shear torque arm
E	strain gauges
F	calibration torque arm
G	central spindle
H	bearing
J	fixed frame
K	reduction gear
L	drive motor
H	counterweight attachment collar
N	counterweights
P	additional weights
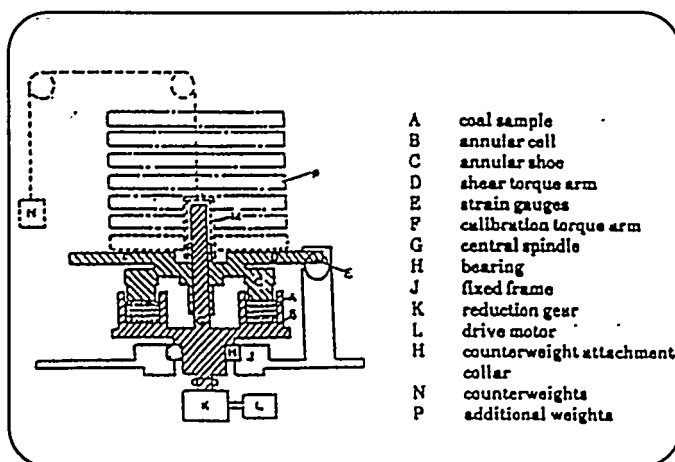
Figure 1. Walker Annular Shear Cell /3/.
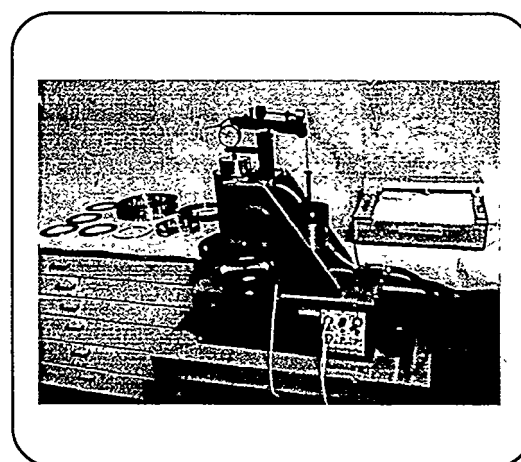
Figure 2. Walker Annular Shear Cell.

2. DETERMINATION OF CHARACTERISTICS

In practice, the sample is laid on the lower ring, consolidated by the upper ring with wished consolidation and shore rotating the lower ring, until it is shorn. The power required for shearing (and possible movement upwards) is measured. By shearing bulk solids at several normal loads of a certain consolidation the equivalent shear strengths are obtained. As a result, the yield locus at each consolidation can be determined for the material. Then the maximum stress caused by devergent main stresses (shear and compression stresses) in the material can be determined by means of so-called Mohr's circles drawn at the yield locus. The unconfined yield strength (f_c) caused by this maximum strength for the bulk solids is also obtained. In addition, the cohesion, internal friction and effective internal friction of the material are obtained at a wished consolidation. An example of calculation results for one consolidation is shown in Figure 3.
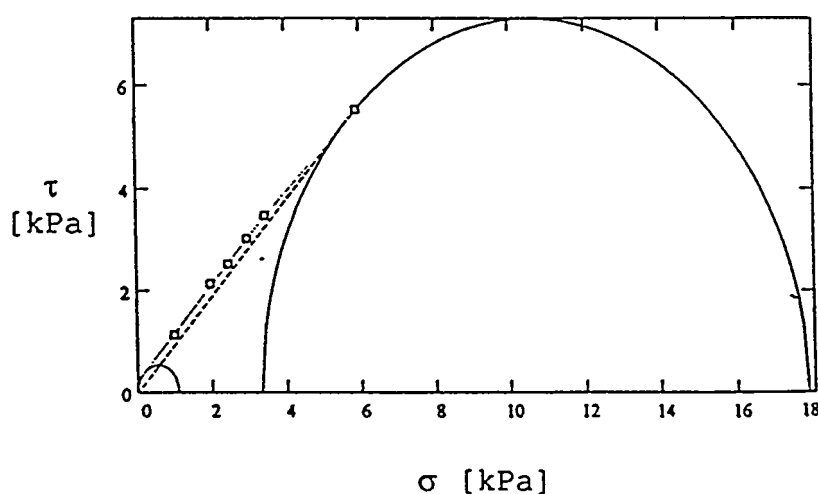
Figure 3. Output of a shear test with coal (consolidation 9.81 kPa).

By carrying out the measurements at several different consolidations the flow curve and function (FF) can be determined for the fuel. The output of a shear testing series at four different consolidations is presented in Table 1. The table also includes the other values obtained in the testing, such as internal friction (ϕ), effective internal friction (δ) and cohesion (c).

The inverse value (N_{FF}) of the derivative of the linearized flow curve (i.e. figure 4) is generally used for indicating the flow of the material, the higher value always indicating superior flow properties. The limit values are as follows (Jenike 1962) /1/. < 2 = the material does not flow at all. > 10 = the material flows easily. The wall yield locus that indicates friction conditions at the limit point can be drawn by determining the friction between the construction material of the handling equipment and the feed material at different loads. By drawing the specific flow curve of the handling equipment and the flow curve of the feed material on the same axis of coordinates. The critical point, indicating the unconfined strength (f_c) in the handling equipment, is obtained at the shear point of these curves. For example, the bins should be designed so that the strength of the fuel arch (σ_a) is exceeded in its discharge opening.

Table 1. Output of shear testing coal (Annular Shear Cell (Walker)). Moisture 2.53 %, fraction < 5 mm).

$$Y = \begin{array}{ccccccc}
\text{K} \\
\text{o} \\
\text{n.} & \phi & \delta & \text{c} & \sigma 1 & \text{fc} \\
\left[\begin{array}{cccccc}
0.000 & 4.000 & 41.848 & 42.930 & 0.168 & 11.919 & 0.768 \\
1.000 & 6.000 & 41.813 & 43.237 & 0.234 & 17.836 & 1.085 \\
2.000 & 8.000 & 41.188 & 42.945 & 0.406 & 23.204 & 1.872 \\
3.000 & 10.000 & 42.185 & 43.428 & 0.372 & 29.338 & 1.803 \\
\end{array}\right] \\
\text{kg} & \text{o} & \text{o} & \text{kPa} & \text{kPa} & \text{kPa}
\end{array}$$

$N_{FF} = 14.96$ = Flow function

fc
[kPa]

$\sigma 1$ [kPa]
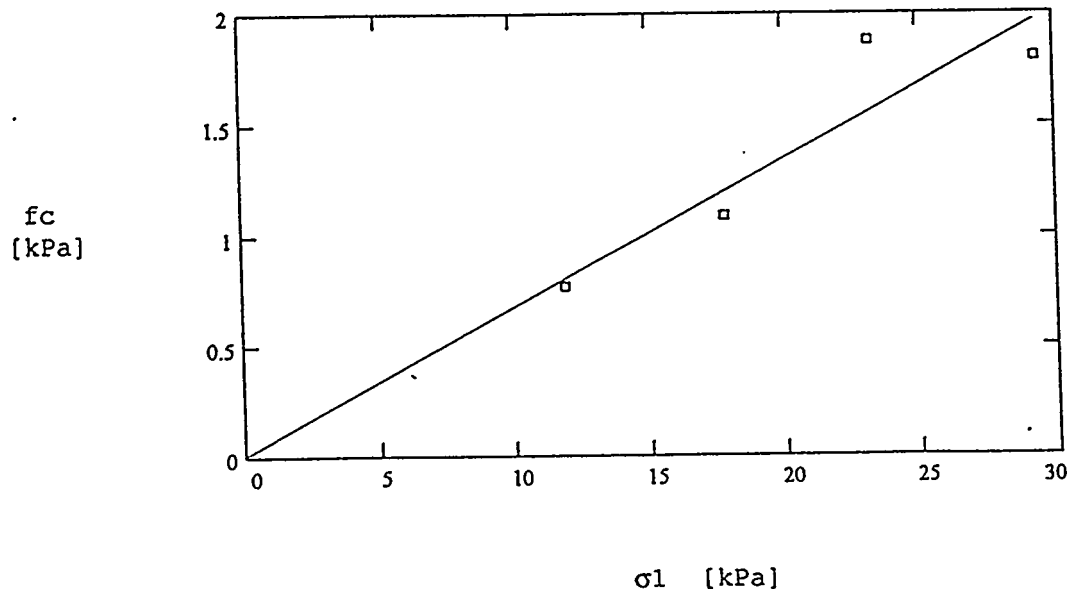
Figure 4. Flow curve of coal (0 h) CRE.

2.1 Characteristics of fuels

Results obtained for the fuels used in the shear cell tests are presented in Table 2 and the characteristics of all fuels used in flowability tests in Table 3. The coals with different moisture contents required for the tests were produced by spraying additional water, as much as required for additional moistening, into dry coal. After moistening the samples were let to stabilise in a tight vessel for about two weeks, after which their moisture content was determined and the determinations required were carried out.

Table 2. Shear tests.

Fuel	N_{FF}-value 22 °C 0.0h	N_{FF}-value 22 °C 1.0h	N_{FF}-value 140 °C 0.0h	N_{FF}-value 140 °C 1.0h	Minimum outlet diameter (m) Conical hopper Stainless steel	Max.conical mass flow wall angles (degrees from vertical) Stainless steel
Forest residue (d50=0.22mm)*	3.8				1.6	21°
Forest residue (d50=0.22mm)*		2.7			2	23°
Forest residue (d50=0.22mm)*			3.6		0.11	21°
Forest residue (d50=0.22mm)*				3	.2	23°
Forest residue < 5mm	11.5				0.69	34°
Forest residue <5mm		7.5			0.61 Rusty steel	13° Rusty steel
Coal (MC=2.54%) (d50=0.95mm	14.9				0.13	17
Coal (MC=2.54%) (d50=0.95mm		14.5			0.40	17
Coal (MC=4.19%) (d50=0.95mm	7.8				0.34	28
Coal (MC=6.6%) (d50=0.95mm 0h at rest	6.2				0.13	25
Coal (MC=6.6%) (d50=0.95mm 1h at rest		12.3			0.64	23
Coal (MC=12.0%) (d50=0.95mm 0h at rest	4.6				0.79	31

* Tested by Jenike & Johanson, inc.USA (Appendix 1)

Table 3. Characteristics of fuels used in flowability tests.

	Forest residue	Coal*	Straw (dried)	Bagasse
Particle size, D50, mm	0.22	~0.95	<3	<4
Moisture content, %	6.9	3.9	11.6	5.84
Ash content, % of dry matter	2.6	16.2	4.7	15.2
Volatiles, % of dry matter	78.8	31.9	77.7	71.1
C content, % of dry matter	53.1	63.4	47.3	42.4
H content, % of dry matter	5.9	4.0	5.8	5.2
N content, % of dry matter	0.3	1.1	0.6	0.3
O content (by difference), %	38.1	8.5	41.6	36.9
S content (total)	-	1.6		0.03
Chlorine	-	0.21		
Density,loose (kg/m³)	216.8	840.3	67.4	59.7
Density,compacted(kg/m)	273.8	910,9	91.3	61.4
*-Proximate and ultimate analysis given by British Coal				

2.3. Use of characteristics in bin dimensioning

When the internal friction and effective internal friction, volume weight and unconfined yield strength are known, for example, the minimum dimensions of the discharge opening of the bin can be calculated on the basis that the gravitational flow of the bulk solids is able to break the arch formed in the discharge opening. The specific flow curves of different bins are also required to determine the unconfined yield strength (f_c) in the bin or in the handling equipment, regarding also the wall declination of the bin. These curves are presented, for example, by Jenike (1962) /1/. F_c values applied to fuels by forces developed in the bin can also be determined by calculating the pressures formed by the fuel at different points of the bin during discharge, filling and storage. The size of the minimum discharge opening (B_{min}) can then be calculated using, for example, the following generally known formula:

$$B_{min} = \frac{m \cdot f_c}{\rho \cdot g} \sin 2\delta$$

m = 1 (rectangular opening)
m = 2 (circular opening)
f_c = unconfined yield strength
 δ = internal effective angle of friction
 ρ = bulk density
 g = gravitational acceleration

Minimum discharge openings calculated on this basis are presented in Table 2. As can be seen forest residue may be a rather poorly flowing fuel. The flow is generally the poorer the higher the moisture content.

2.4 Variations in flow properties of fuels

In general, the N_{FF} value is reduced rather systematically when the moisture content increases, i.e. the fuel flow malfunctions are increased by an increase in moisture content, as changes in the load applied to the fuel by the handling equipment and as a consequence changes in stresses weaken the flow sharply. On the other hand, a high N_{FF} value indicates that the fuel is not very sensitive to load variations and is in that sense a reliable indicator of flow properties, if the equipment is correctly dimensioned. The variation of N_{FF} values for the tested fuels is also shown in Table 2. Friction between fuel and the wall materials required for the design of bins, determined with the Walker annular shear cell method, are shown in Figures 5 - 13. As can be seen from the figures, the friction is much greater at small consolidation pressures and decreases while the loading increases. This means in practice that when the bin is wanted to be discharged completely, the consolidating load is at the end very small and the friction between the fuel and the wall is smaller compared to the initial situation. As a consequence the bin does not become completely empty, if it has not been designed on correct wall friction values. On the other hand, the storage time had an effect on the friction coefficient in such a way that the value of friction coefficient was usually increased clearly over the storage time of one hour used in the tests, excepting for very moist coal samples. In the example dimensionings for bins presented in Appendix 2, pages 1 - 8, a value obtained with small loading (=max. value) was used for the friction angle. Flow-technical characteristics required for the design of bins, conveyors and other handling equipment of bulk solids, determined with the FEM method, are presented in Table 4. It was of interest to notice at coal tests that when the moisture content was 4.2% , the flowability of coal was worse than that of the coals with had moisture contents of 2.5 and 7.0 % (the angle of repose was steep, the friction between the fuel and the wall material was high, and the angle of flow was steep too). This may be due to the fact that the moisture content is so high that it increases the internal friction and the cohesion of coal, while the surface moisture is so low that the water does not act as lubricating agent on the surfaces of particles and between the fuel and the wall material.

Figure 14 shows that it is very important to carry out a sufficiently wide survey of the flow properties of fuels to guarantee a reliable operation of the handling equipment even when the quality of the fuel is varying. Figure 15 shows the wall angle (θ_c) of the conical hopper and the minimum outlet (B).

Details of shear tests carried out with the Jenike test equipment for forest residue fuels are given in Appendix 1, and an example of bin dimensioning on the basis of flow tests in Appendix 2. Determination methods of the FEM flow tests are presented in Appendix 3.

Table 6. Flow-technical characteristics of fuels (FEM).

Fuel	Angle of repose degrees	Angle of wall friction (FEM) Rusty steel degrees	Angle of wall friction(FEM) Stainless steel degrees	Angle of flow degrees	Bulk density (loose) kg/m^3
Forest residue<0.2mm (MC.=7.1%)	52.2	33.8	24.1	>96 No flow	216.8
Forest residue <5mm (MC.=6.14%)	34.6	28	12.1	94.6	260
Coal< 5mm (MC.=2.5%)	24.9	23.8	17.9	46.8	825.1
Coal< 5mm (MC.=4.2%)	40.3	25.4	22.1	55.4	840.3
Coal< 5mm (MC.=7.0 %)	32.2	25.4	20.7	50.5	861
Coal< 5mm (MC.=12.0 %)	28.3	30.5	20.3	>96 No flow	901.6
Straw < 3mm (MC.=3.3%)	57.8	29.1	21.8	>96 No flow	67.4
Straw < 3mm (MC.=15.7%)	59.5	32.4	26.6	>93.1 No flow collapsed	82
Straw < 10mm (MC.=9.4%)	81	24.1	17	>91.9 No flow collapsed	79
Bagasse<4mm (MC.=5.84%)	63.8	21.5	15.5	>96 No flow	59.7

Wall friction
Forest residue D50=0.22mm [MC.=7.1%]
Biosafe
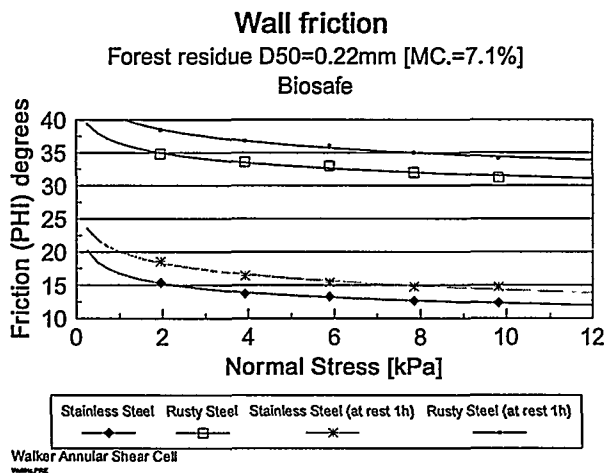
Figure 5. Friction between forest residue (mc. 7.1 %) and the wall material (Walker shearcell).
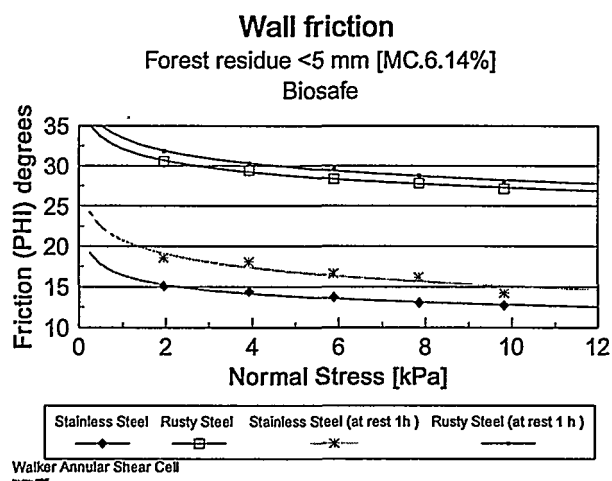
Figure 6. Friction between forest residue (mc. 6.14 %) and the wall material (Walker shear cell).
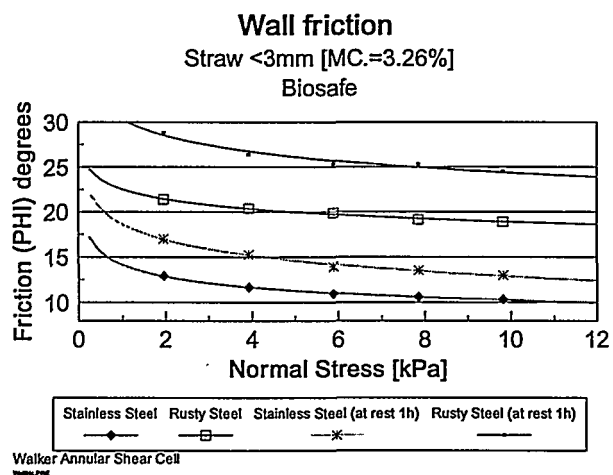
Figure 7. Friction between straw (mc. 3.26 %) and the wall material (Walker shear cell).

Wall friction
Straw <10mm [MC.=9.43%]
Biosafe
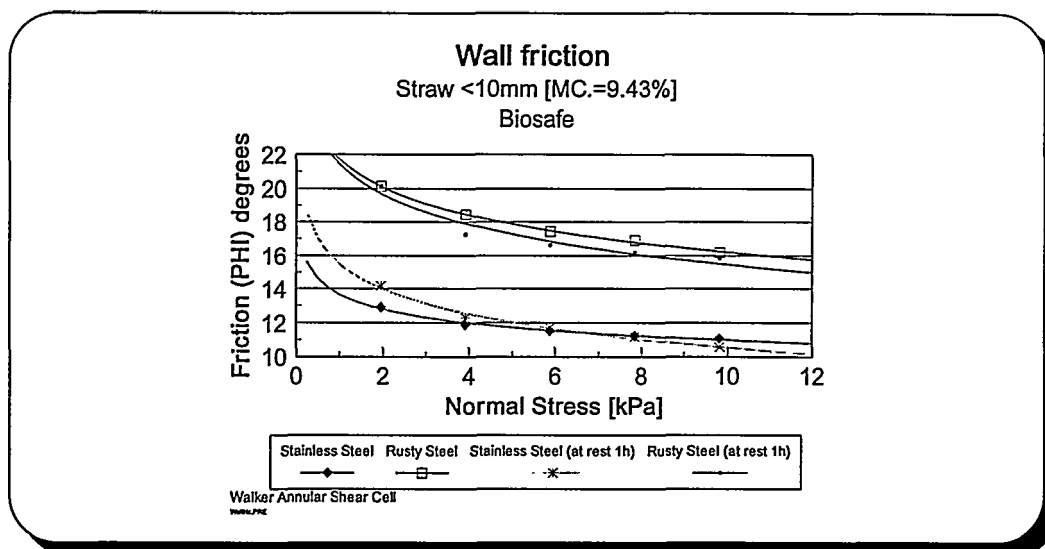
Figure 8. Friction between straw (mc.9.43%) and the wall material (Walker shear cell).

Wall friction
Straw <5mm [MC.=15.73%]
Biosafe
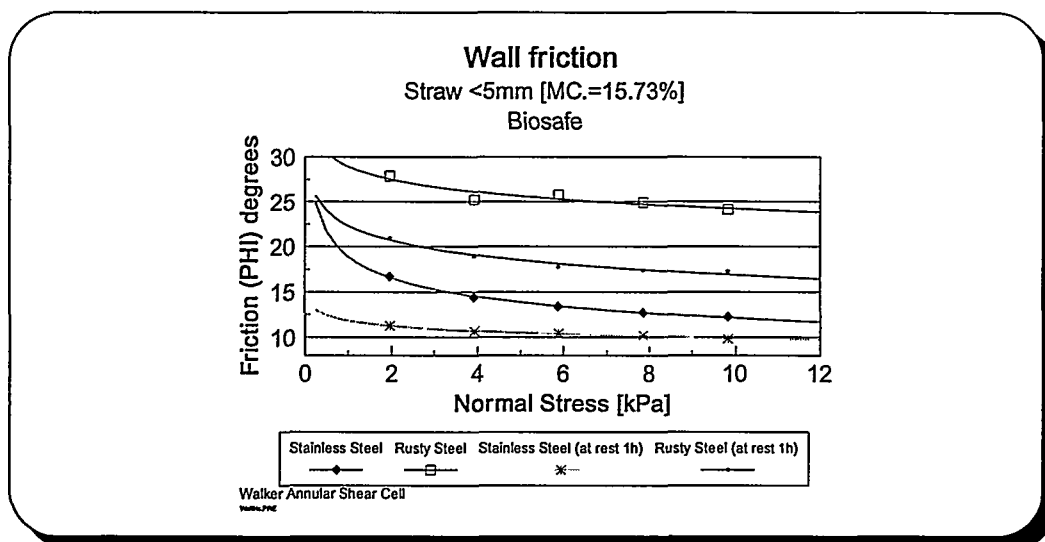
Figure 9. Friction between straw (mc. 15.73 %) and the wall material(Walker shear cell).

Wall friction
Coal<5 mm [MC.2.55%]
Biosafe
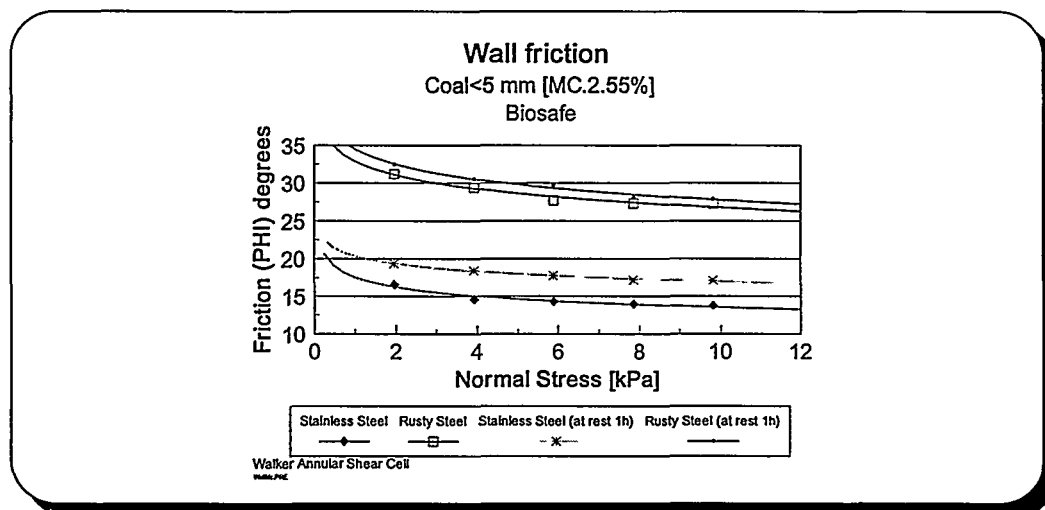
Figure 10. Friction between coal (mc. 2.55 %) and the wall material (Walker shear cell).

Wall friction
Coal<5 mm [MC.4.19%]
Biosafe
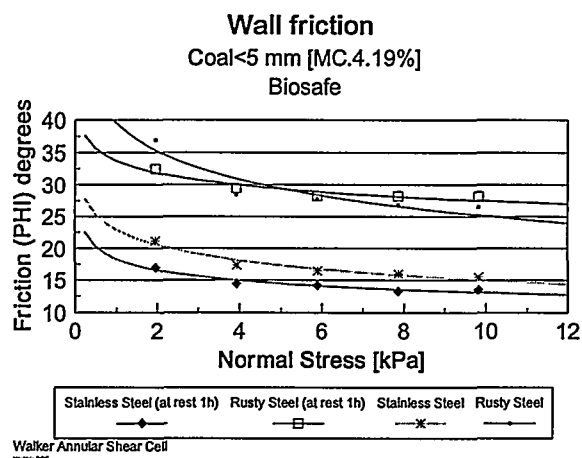
Figure 11. Friction between coal (mc. 4.19 %) and the wall material (Walker shear cell).

Wall friction
Coal<5 mm [MC.6.59%]
Biosafe
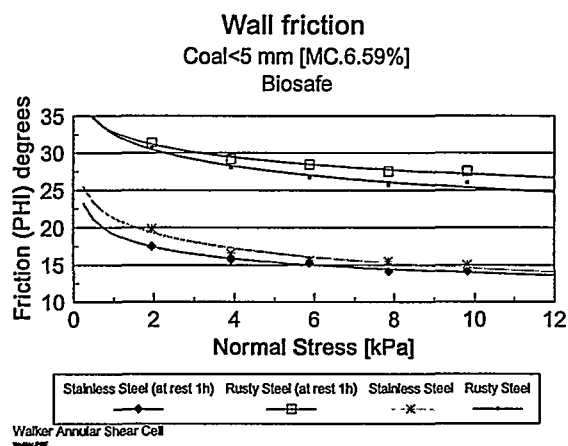
Figure 12. Friction between coal (mc. 6.59 %) and the wall material (Walker shear cell).

Wall friction
Coal<5 mm [MC.11.94%]
Biosafe
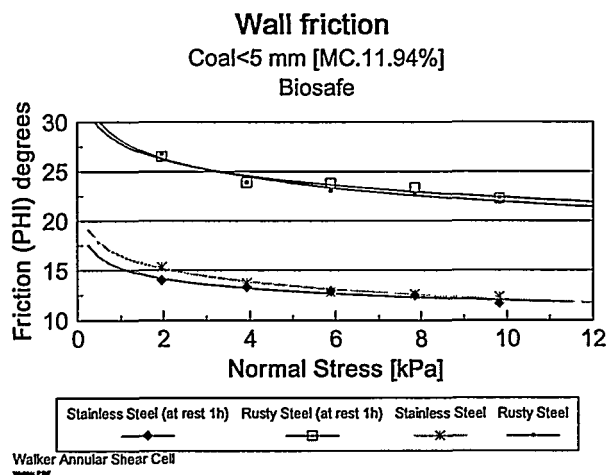
Figure 13. Friction between coal (mc. 11.94 %) and the wall material (Walker shear cell).
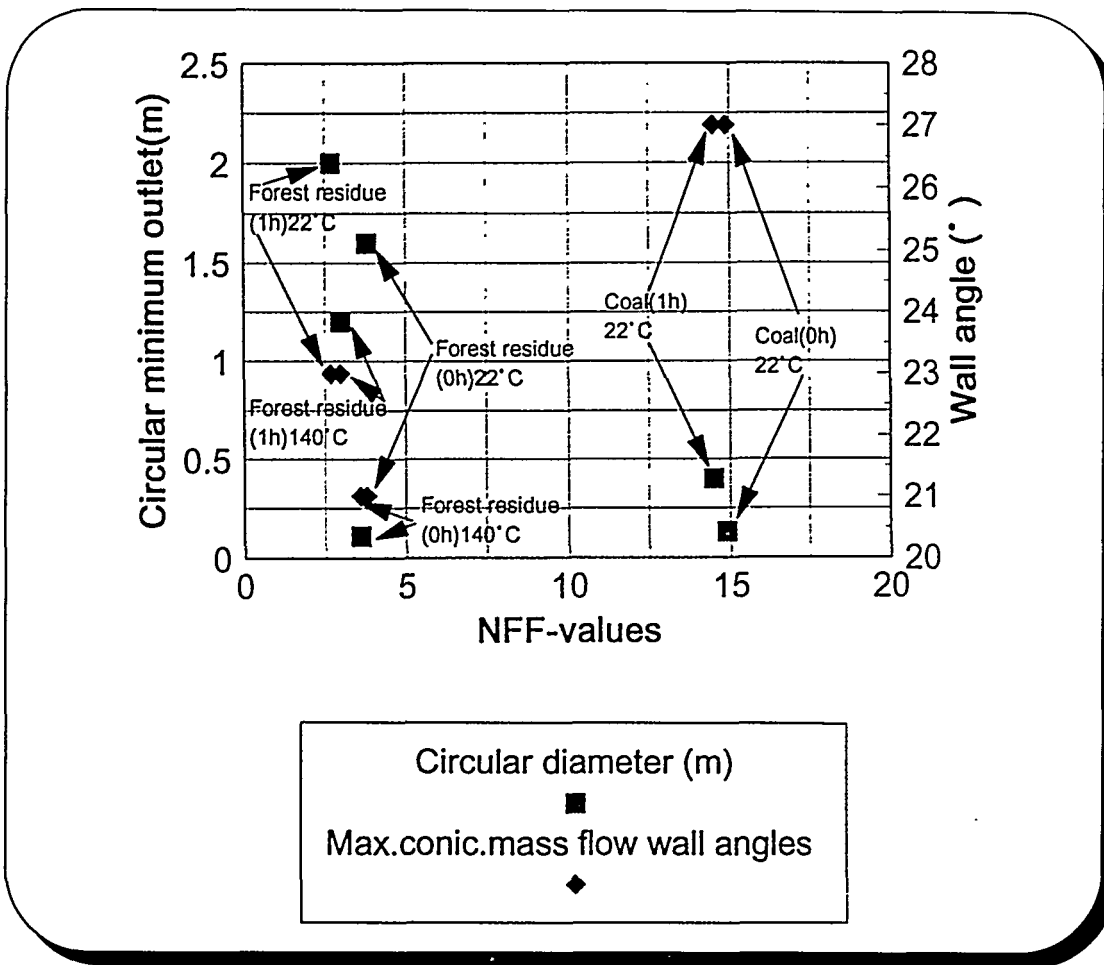
Figure 14. Minimum discharge openings required by different fuels.
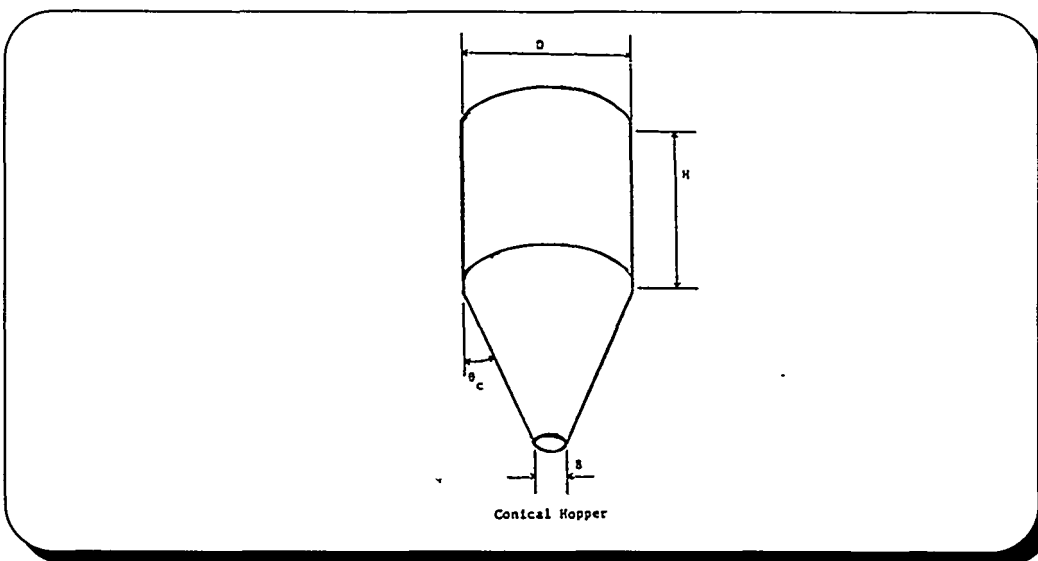
Figure 15. The wall angle (θ_c) of the conical hopper and minimum outlet (B).

3. CONCLUSIONS

When selecting fuel grades for testing on the basis of which the handling equipment will be dimensioned, changes in the fuels during the handling process should be considered. The fuel is subjected for example to mechanical (screws, pneumatic transport, etc.) or thermal (drying) loads, and these usually change flow-technical properties of the fuel. The proportion of fines - which impairs flow properties - is increased in fuel by mechanical handling. Hence, it is of crucial importance that the fuel grades are the real conditions and changes in the fuel properties during earlier handling are also considered in flowability tests.

It was found out that the shear test method was not applicable to straw, as the structure of the fuel was as elastic and non-stabile that the consolidation pressure did not stabilize but varied over the whole testing cycle. As a consequence it was not possible to measure the shear strength reliably.

The tests with the other fuels indicated that the shear test method can well be applied in the design of conical hoppers and in the dimensioning of minimum discharge openings.

The shear tests indicated that the flow characteristics of coal and coarse forest residue chips are good compared, for example, with those of straw, bagasse or fine forest residue chips. The flow characteristics of fine forest residue chips being hot or after hot storage were surprisingly superior to those after cold storage. This may be due to an improvement in the flow characteristics in hot storage due to drying. Secretion of waxy substances to the surface of particles, which usually results in weakening of flowability, did not apparently occur to any significant degree in these conditions. The flow characteristics of the fuels tested got clearly worse when the storage time was extended.

The determination of handling-technical characteristics with the FEM method was usually well suited for the fuels tested. However, it was not possible to obtain reliable results for the flow angles of small-bulk-density, very moist or otherway poorly flowing fuels. This was apparently due to too small dimensions of the measuring equipment. For this reason, it was not possible to determine the exact value of flow angle, i.a., for straw, bagasse, fine forest residue and very moist coal.

REFERENCES

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3. Bird, D.A., Cammack, P. & Sproson, J. C. Coal handlability and the design of storage bunkers for coking smalus and power station blends. NCB/MRDE.

FLOW PROPERTIES TEST REPORT

VTT Fuel and Processing Technology

932931

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STORAGE AND FLOW OF SOLIDS

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INTRODUCTION

This test report describes the flow properties of your material. These properties are expressed in terms of bin dimensions required to ensure dependable flow, maximum hopper angles for mass flow and, if tested, minimum chute angles and critical discharge rates through bin outlets. All dimensions represent limiting conditions for flow; therefore, larger outlets, steeper hoppers and chutes, and flow rates below critical are acceptable. If your material is one which will compact excessively in a large bin, the largest diameter or width and the height of the cylinder to limit this compaction are also given.

In case you are unfamiliar with the use of this type of data, an Appendix follows the main body of the report. Most of the symbols used in the report are shown in the figures on pages A16 to A18. A Glossary of Terms and Symbols is provided on pages A12 to A15.

GENERAL COMMENTS

A sample of wood dust was received from VTT for testing. Tests were run at 22°C and 140°C at the materials' *as received* moisture content, determined to be 7.24%. Moisture values quoted in this report have been determined by drying samples at 107°C for two hours in a forced convection oven. The loss in weight of the sample divided by its original weight before drying is denoted as the "moisture".

Cohesive strength tests

Direct shear tests were run to determine the material's flow function (cohesive strength). This is used to calculate minimum outlet dimensions to prevent arching and ratholing. This material is capable of forming a stable rathole in a funnel flow bin; therefore, a mass flow bin is recommended. Two main considerations in the design of a mass flow bin are:

- the size of the outlet required to prevent arching and achieve the required discharge rate
- the smoothness and steepness of the hopper walls required to allow the material to flow along them.

Based on these tests, the following outlet diameters are required to prevent arching in a mass flow bin:

	Outlet diameter to prevent arching in a mass flow bin	
	continuous flow	1 hr. storage
Material at 22°C	1.6 m	2.0 m
Material at 140°C	0.11 m	1.2 m

However, it was noted that this is a difficult material to test using direct shear. We observed that the inherent springback or elasticity of the wood dust gives the material an "apparent strength." This strength is different than the cohesive strength normally associated with a bulk solid in that the strength is reduced when the loading is removed. This is likely due to the motion of the particles during springback.

Therefore, to investigate this further, we ran hopper tests simulating continuous flow and one hour storage at rest at room temperature. Based on a single trial at each condition, the minimum slot width to allow an arch to fail is 6 cm during continuous flow and 5 cm after one hour storage at rest. This corresponds to outlet diameters of about 13 cm and 11 cm, respectively.

Wall friction tests

Wall friction angles were determined on the wall materials listed below. As an example of the test results, if a conical hopper with a 0.5 m diameter opening were lined or fabricated using the materials listed below, the following wall angles would be required for mass flow. (Note that hoppers with elongated outlets require significantly less steep angles than cones.)

	Maximum recommended conical mass flow wall angles* (degrees from vertical)	
	continuous flow	after 1 hr. storage at rest
Material at 22°C	21°	21°
Material at 140°C	23°	23°

* The maximum recommended wall angle may vary depending on outlet size. The angles specified here apply only for the given outlet size, which may not be sufficiently large to prevent arching of the material. The maximum recommended wall angles should be selected from the appropriate table of the Flow Properties Test Report, based on the actual outlet size for a given design.

SUMMARY OF TESTS PERFORMED

This report presents various flow property test results as indicated for the following material(s) :

BULK MATERIAL	MATERIAL ID #	DESCRIPTION	PARTICLE SIZE	MOISTURE CONTENT
1	18771	WOOD DUST	As Rec'd	As Rec'd(7.24%)
2	18778	WOOD DUST	As Rec'd	As Rec'd(7.24%)

BULK MATERIAL	TIME hr	TEMPERATURE deg C	SIEVE ANALYSIS	BIN DIM	BULK DENSITY	HOPPER ANGLES	CHUTE ANGLES	FLOW RATE	OTHER
1	.0	22		X	X	X			
	1.0	22		X		X			
2	.0	140		X	X	X			
	1.0	140		X		X			

3

<u>BULK MATERIAL 1: WOOD DUST</u>

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd(7.24%)

<u>SECTION I. BIN DIMENSIONS FOR DEPENDABLE FLOW</u>

Storage Time at Rest   .0 hrs
Temperature   22 deg C

<u>PART A. BINS WITH UNLIMITED MAXIMUM SIZE</u>

<u>Optimum Mass Flow Dimensions</u>

P-Factor	BC meters	BP meters
1.00	1.60	.77
1.25	1.74	.83
1.50	1.94	.91
2.00	2.61	1.15

<u>Funnel Flow Dimensions</u>

P-Factor	BF (meters)	EH=	.50	1.00	2.5	5.0	10.0	11.9meters
			Critical Rathole Diameters, DF (meters)					
1.00	.96		5.0	5.7	8.5	13.4	23.5	27.3
1.25	1.16		5.1	6.1	9.6	15.7	28.1	32.8
1.50	1.49		5.3	6.5	10.7	17.9	32.6	38.2
2.00	***		5.6	7.3	12.8	22.3	41.5	48.7

*** Denotes unassisted gravity flow is impossible. However, widths of only
    up to   4.1 meters were simulated by our tests. If larger widths
    are practical for your application, further testing at higher pressures
    might reveal conditions under which unassisted gravity flow is possible.

<div align="center">TERMS</div>

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

<div align="center">4</div>

BULK MATERIAL 1:   WOOD DUST

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd(7.24%)

Storage Time at Rest   1.0 hrs
Temperature   22 deg C

PART A.   BINS WITH UNLIMITED MAXIMUM SIZE

Optimum Mass Flow Dimensions

P-Factor	BC meters	BP meters
1.00	1.96	.93
1.25	2.30	1.06
1.50	2.82	1.24
2.00	6.18	2.10

Funnel Flow Dimensions

P-Factor	BF (meters)	EH=	.20	.50	1.00	2.5	5.0	8.2meters
			Critical Rathole Diameters, DF (meters)					
1.00	1.36		5.1	5.6	6.7	10.5	17.1	25.7
1.25	2.04		5.2	5.8	7.2	11.9	20.1	30.8
1.50	***		5.2	6.0	7.8	13.4	23.1	35.7
2.00	***		5.4	6.5	8.9	16.3	28.9	45.4

*** Denotes unassisted gravity flow is impossible. However, widths of only
    up to   3.9 meters were simulated by our tests. If larger widths
    are practical for your application, further testing at higher pressures
    might reveal conditions under which unassisted gravity flow is possible.

TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

BULK MATERIAL 1: WOOD DUST

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd(7.24%)

SECTION II. SOLIDS DENSITY

TEMPERATURE   22 deg C

BULK DENSITY

The bulk density, GAMMA, is a function of the major consolidating
pressure, SIGMA1, expressed in terms of effective head, EH.

EH (meters)	.2	.5	1.0	2.5	5.0	10.0	20.0	30.0
SIGMA1 (kPa)	0.	1.	2.	7.	14.	31.	65.	102.
GAMMA (kg/m^3)	214.3	234.0	250.1	273.1	291.8	311.9	333.3	346.6

COMPRESSIBILITY PARAMETERS

Bulk density, GAMMA, is a function of the major consolidating pressure
SIGMA1, as follows:

GAMMA is the greater of $GAMMA0 (SIGMA1/SIGMA0)^{BETA}$ and GAMMAM.

For GAMMA between 249.5 and 354.0 kg/m^3

     GAMMA0 =   221.82 kg/m^3

     SIGMA0 =   .62 kPa

     BETA =   .08751

Minimum bulk density GAMMAM = 194.0 kg/m^3

BULK MATERIAL 1: WOOD DUST

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd(7.24%)

ECTION III. MAXIMUM HOPPER ANGLES FOR MASS FLOW

ALL MATERIAL: 304 #2B Finish Stainless Steel Sheet
TORAGE TIME AT REST .00 hrs
EMPERATURE   22 deg C

HOPPER ANGLES FOR VARIOUS HOPPER SPANS

ia of Cone (meters)	.26	.50	1.00	2.50	5.00	7.50	10.00	14.55
idth of Oval (meters)	.15	.28	.55	1.36	2.69	4.02	5.35	7.75
IGMA (kPa)	.2	.4	1.	3.	6.	9.	13.	20.
IGMA1 (kPa)	.3	.5	1.	3.	6.	10.	13.	20.
all Friction Angle								
HI-PRIME (deg)	29.	20.	16.	13.	12.	11.	11.	10.
opper Angles								
HETA-P (deg)	24.	34.	39.	42.	43.	44.	44.	45.
HETA-C (deg)	11.	21.	26.	28.	30.	30.	31.	32.

ALL MATERIAL: 304 #2B Finish Stainless Steel Sheet
TORAGE TIME AT REST 1.00 hrs
EMPERATURE   22 deg C

o time effect! Use results from test having storage time at rest of 0.0 hrs.

7

BULK MATERIAL 2: WOOD DUST

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd(7.24%)

SECTION I. BIN DIMENSIONS FOR DEPENDABLE FLOW

Storage Time at Rest   .0 hrs
Temperature   140 deg C

PART A. BINS WITH UNLIMITED MAXIMUM SIZE

Optimum Mass Flow Dimensions

P-Factor	BC meters	BP meters
1.00	.11	.06
1.25	.12	.06
1.50	.14	.06
2.00	.19	.08

Funnel Flow Dimensions

P-Factor	BF (meters)	EH=	.20	.50	1.00	2.5	5.0	9.4 meters
			Critical Rathole Diameters, DF (meters)					
1.00	.07		1.00	2.0	3.6	7.9	13.3	18.9
1.25	.09		1.14	2.3	4.3	9.3	15.2	20.3
1.50	.12		1.28	2.7	5.0	10.6	16.7	21.1
2.00	.57		1.6	3.4	6.2	12.8	18.8	21.8

TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

BULK MATERIAL 2: WOOD DUST

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd(7.24%)

Storage Time at Rest   1.0 hrs
Temperature   140 deg C

PART A. BINS WITH UNLIMITED MAXIMUM SIZE

Optimum Mass Flow Dimensions

P-Factor	BC meters	BP meters
1.00	1.15	.55
1.25	1.33	.61
1.50	1.61	.71
2.00	3.16	1.14

Funnel Flow Dimensions

P-Factor	BF (meters)	EH=	.20	.50	1.00	2.5	5.0	9.4 meters
			Critical Rathole Diameters, DF (meters)					
1.00	.79		4.7	5.6	7.4	12.4	18.6	25.0
1.25	1.17		4.8	6.0	8.2	14.0	20.8	26.5
1.50	2.51		4.9	6.4	9.0	15.4	22.5	27.4
2.00	***		5.2	7.2	10.4	18.0	24.9	28.0

*** Denotes unassisted gravity flow is impossible. However, widths of only
    up to   4.2 meters were simulated by our tests. If larger widths
    are practical for your application, further testing at higher pressures
    might reveal conditions under which unassisted gravity flow is possible.

TERMS
P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

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BULK MATERIAL 2: WOOD DUST

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd(7.24%)

SECTION II. SOLIDS DENSITY

TEMPERATURE 140 deg C

BULK DENSITY
The bulk density, GAMMA, is a function of the major consolidating
pressure, SIGMA1, expressed in terms of effective head, EH.

EH (meters)	.2	.5	1.0	2.5	5.0	10.0	20.0	30.0
SIGMA1 (kPa)	0.	1.	2.	6.	14.	30.	64.	99.
GAMMA (kg/m^3)	199.9	220.0	236.6	260.5	280.1	301.2	323.9	338.0

COMPRESSIBILITY PARAMETERS

Bulk density, GAMMA, is a function of the major consolidating pressure
SIGMA1, as follows:

GAMMA is the greater of GAMMA0 (SIGMA1/SIGMA0)^{BETA} and GAMMAM.

For GAMMA between 238.7 and 346.9 kg/m^3

     GAMMA0 = 208.85 kg/m^3

     SIGMA0 =   .62 kPa

     BETA = .09488

Minimum bulk density GAMMAM = 167.4 kg/m^3

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd(7.24%)

SECTION III.   MAXIMUM HOPPER ANGLES FOR MASS FLOW

WALL MATERIAL: 304 #2B Finish Stainless Steel Sheet
STORAGE TIME AT REST   .00 hrs
TEMPERATURE   140 deg C

HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (meters)	.26	.50	1.00	2.50	5.00	7.50	10.00	15.10
Width of Oval (meters)	.14	.27	.55	1.35	2.69	4.03	5.36	8.08
SIGMA (kPa)	.2	.4	1.	3.	6.	9.	12.	20.
SIGMA1 (kPa)	.2	.5	1.	3.	6.	9.	13.	20.
Wall Friction Angle								
PHI-PRIME (deg)	25.	18.	15.	13.	12.	12.	12.	12.
Hopper Angles								
THETA-P (deg)	28.	36.	40.	42.	42.	43.	43.	43.
THETA-C (deg)	15.	23.	26.	28.	29.	29.	30.	30.

WALL MATERIAL: 304 #2B Finish Stainless Steel Sheet
STORAGE TIME AT REST 1.00 hrs
TEMPERATURE   140 deg C

HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (meters)	.90	1.00	2.50	5.00	7.50	10.00	10.72
Width of Oval (meters)	.49	.55	1.36	2.70	4.05	5.38	5.77
SIGMA (kPa)	.8	.9	3.	6.	9.	12.	13.
SIGMA1 (kPa)	.9	1.0	3.	6.	9.	13.	14.
Wall Friction Angle							
PHI-PRIME (deg)	17.	17.	15.	14.	14.	14.	14.
Hopper Angles							
THETA-P (deg)	37.	38.	40.	40.	40.	40.	40.
THETA-C (deg)	24.	25.	26.	27.	27.	27.	27.

BULK MATERIAL: WOOD DUST
PARTICLE SIZE: As Rec'd
MOISTURE % WT: As Rec'd(7.24%)

CREATE: 93/12/09
RUN: 93/12/20

JOB#: 932931
ID#: 18771

generic   JKP

DELTA & PHI RELATIONS

Consolidating Pressure SIGMA1, kPa

FLOW FUNCTION(S)

Consolidating Pressure SIGMA1, kPa

BULK MATERIAL: WOOD DUST
PARTICLE SIZE: As Rec'd
MOISTURE % WT: As Rec'd(7.24%)

CREATE: 93/12/09   JOB#: 932931
RUN: 93/12/20   ID#: 18771

YIELD LOCUS

V1	7.5 kPa
Fc inst	3.2 kPa
Fc 1. hrs	3.2 kPa
Delta	71.3 deg
Phi	65.3 deg

Legend:
- ⊙ Steady State
- ☐ .0 hrs   22 deg C
- △ 1.0 hrs   22 deg C

Normal Load V, N for 6.35 cm cell

BULK MATERIAL: WOOD DUST
PARTICLE SIZE: As Rec'd
MOISTURE % WT: As Rec'd(7.24%)

CREATE: 93/12/09   JOB#: 932931
RUN: 93/12/20   ID#: 18771

YIELD LOCUS

Legend within plot:
- ⊙ Steady State
- □ 0 hrs 22 deg.C
- △ 1.0 hrs 22 deg C

V1	13.7 kPa
Fc inst	4.8 kPa
Fc 1.hrs	6.2 kPa
Delta	63.3 deg
Phi	57.1 deg

Normal Load V, N for 6.35 cm cell

BULK MATERIAL: WOOD DUST
PARTICLE SIZE: As Rec'd
MOISTURE % WT: As Rec'd(7.24%)

CREATE:　93/12/09
RUN:　93/12/20

JOB#: 932931
ID#: 18771

YIELD LOCUS

⊕　Steady State	V1　　20.9 kPa
□　.0 hrs　22 deg C	Fc inst　6.6 kPa
△　1.0 hrs　22 deg C	Fc　1. hrs　8.9 kPa
	Delta　65.5 deg
	Phi　60.6 deg

Normal Load V, N for 6.35 cm cell

BULK MATERIAL: WOOD DUST
PARTICLE SIZE: As Rec'd
MOISTURE % WT: As Rec'd(7.24%)

CREATE: 93/12/09   JOB#: 932931
RUN: 93/12/20   ID#: 18771

YIELD LOCUS

Legend in plot:
○ Steady State
□ .0 hrs 22 deg C

V1	31.46 kPa
Fc inst	9.59 kPa
Delta	64.51 deg
Phi	59.64 deg

Normal Load V, N for 6.35 cm cell
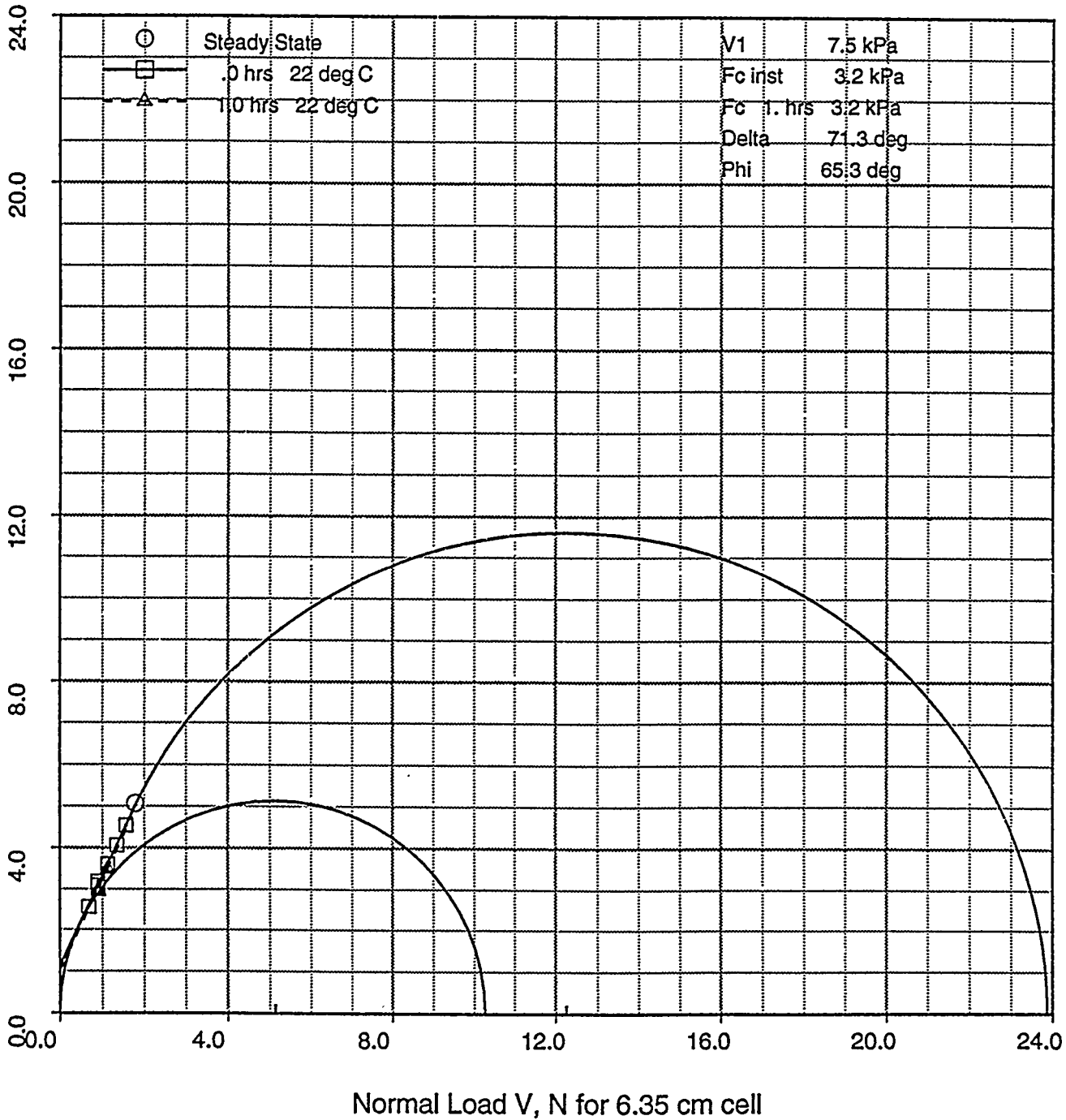
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BULK MATERIAL: WOOD DUST
PARTICLE SIZE: As Rec'd
MOISTURE % WT: As Rec'd(7.24%)
TEMPERATURE: 22 deg C

CREATE: 93/12/09
RUN: 93/12/20

JOB#: 932931
ID#: 18771

BULK DENSITY VS. CONSOLIDATING PRESSURE

Consolidating Pressure SIGMA1, kPa

BULK MATERIAL: WOOD DUST
PARTICLE SIZE: As Rec'd
MOISTURE % WT: As Rec'd(7.24%)
TEMPERATURE: 22 deg C

CREATE: 93/12/09   JOB#: 932931
RUN: 93/12/20   ID#: 18771

WALL YIELD LOCUS

WALL MATERIAL: 304 #2B Finish Stainless Steel Sheet
STORAGE TIME AT REST
  —◯—   0.0 hrs
  --☐--   1.0 hrs

NORMAL STRESS SIGMA, kPa

WALL FRICTION ANGLE

NORMAL STRESS SIGMA, kPa

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BULK MATERIAL: WOOD DUST
PARTICLE SIZE: As Rec'd
MOISTURE % WT: As Rec'd(7.24%)

CREATE: 93/12/16
RUN: 93/12/20

JOB#: 932931
ID#: 18778

DELTA & PHI RELATIONS
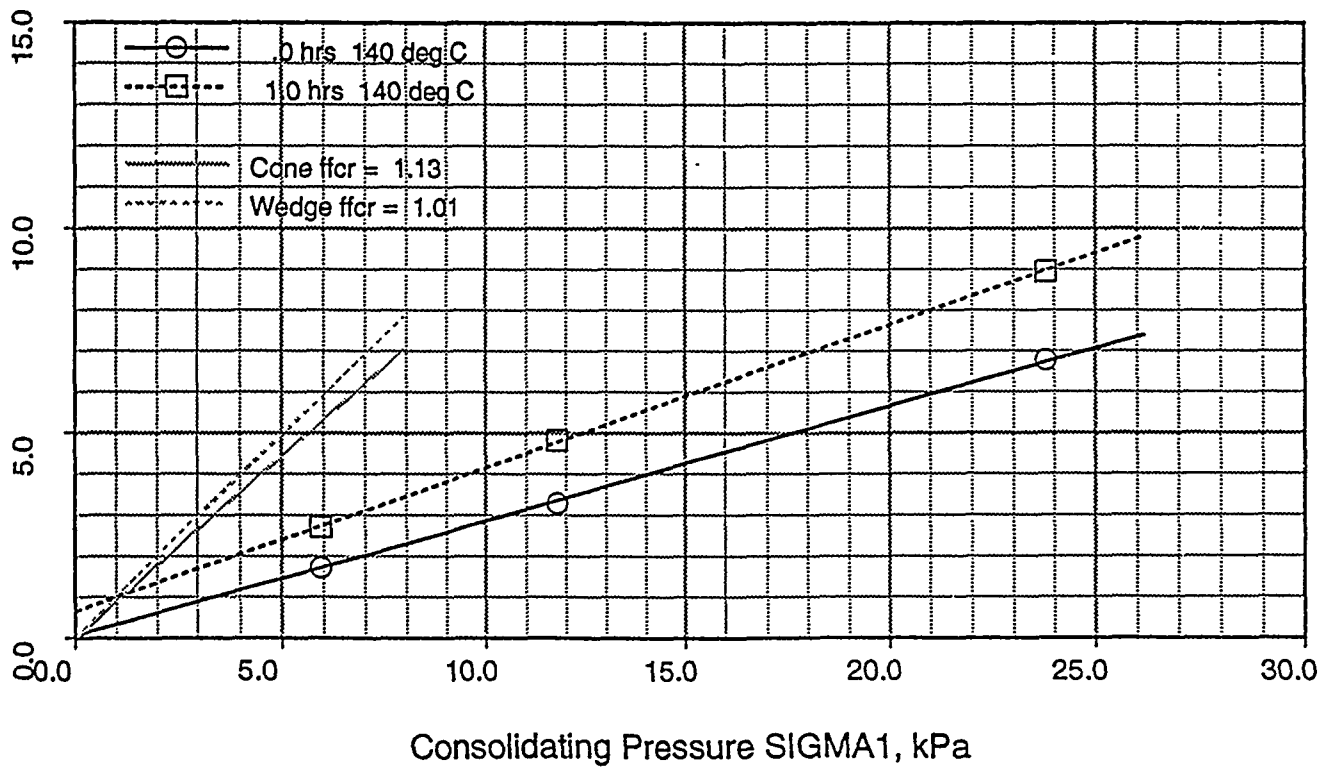
Legend:
- △——— DELTA
- ⊙---- PHI 00 hrs
- ☐—-— PHI 100 hrs

Consolidating Pressure SIGMA1, kPa

FLOW FUNCTION(S)

Legend:
- ⊙——— 0 hrs 140 deg C
- ☐---- 100 hrs 140 deg C
- Cone ffcr = 1.13
- Wedge ffcr = 1.01
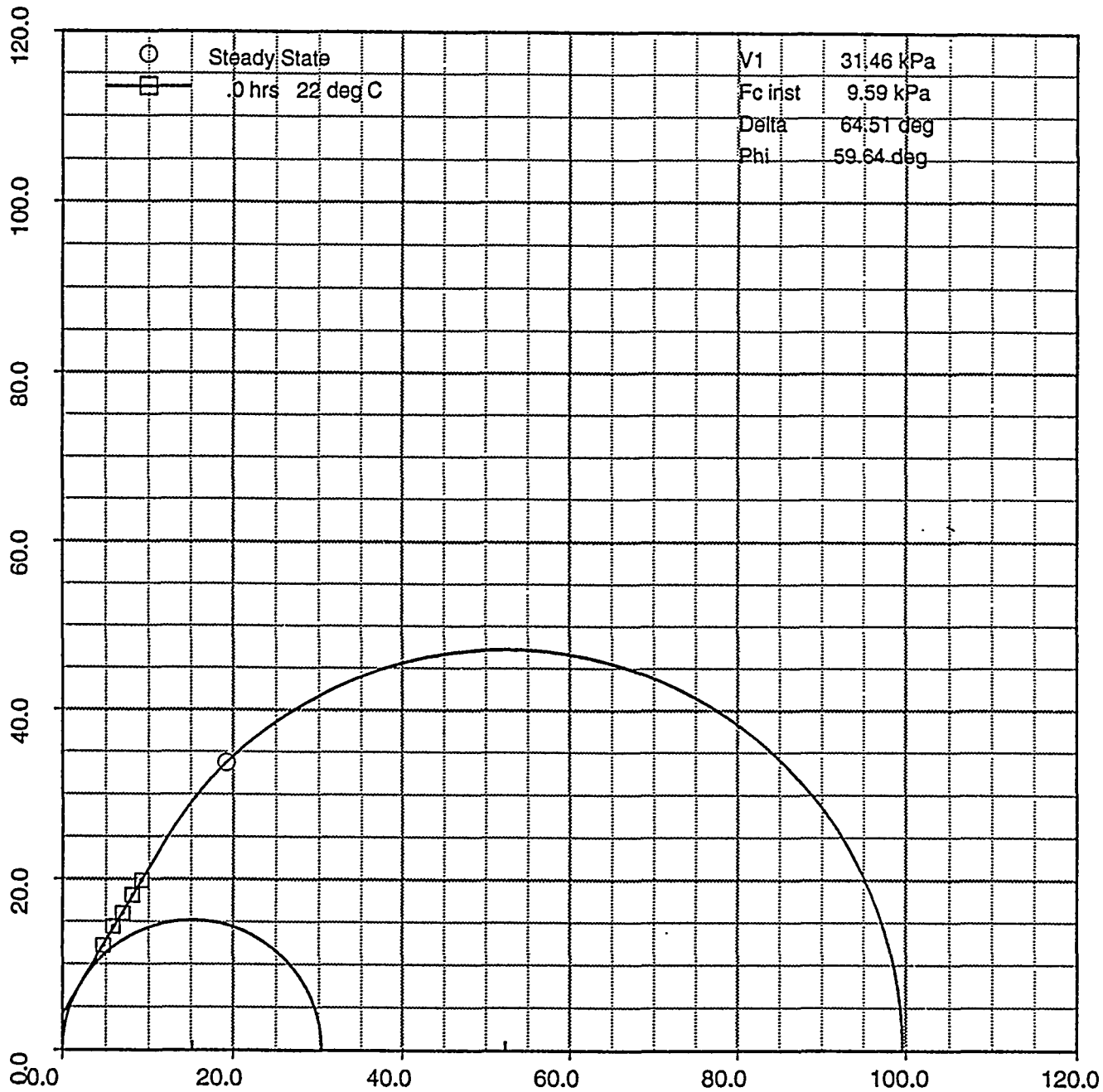
Consolidating Pressure SIGMA1, kPa

BULK MATERIAL: WOOD DUST
PARTICLE SIZE: As Rec'd
MOISTURE % WT: As Rec'd(7.24%)

CREATE: 93/12/16
RUN: 93/12/20
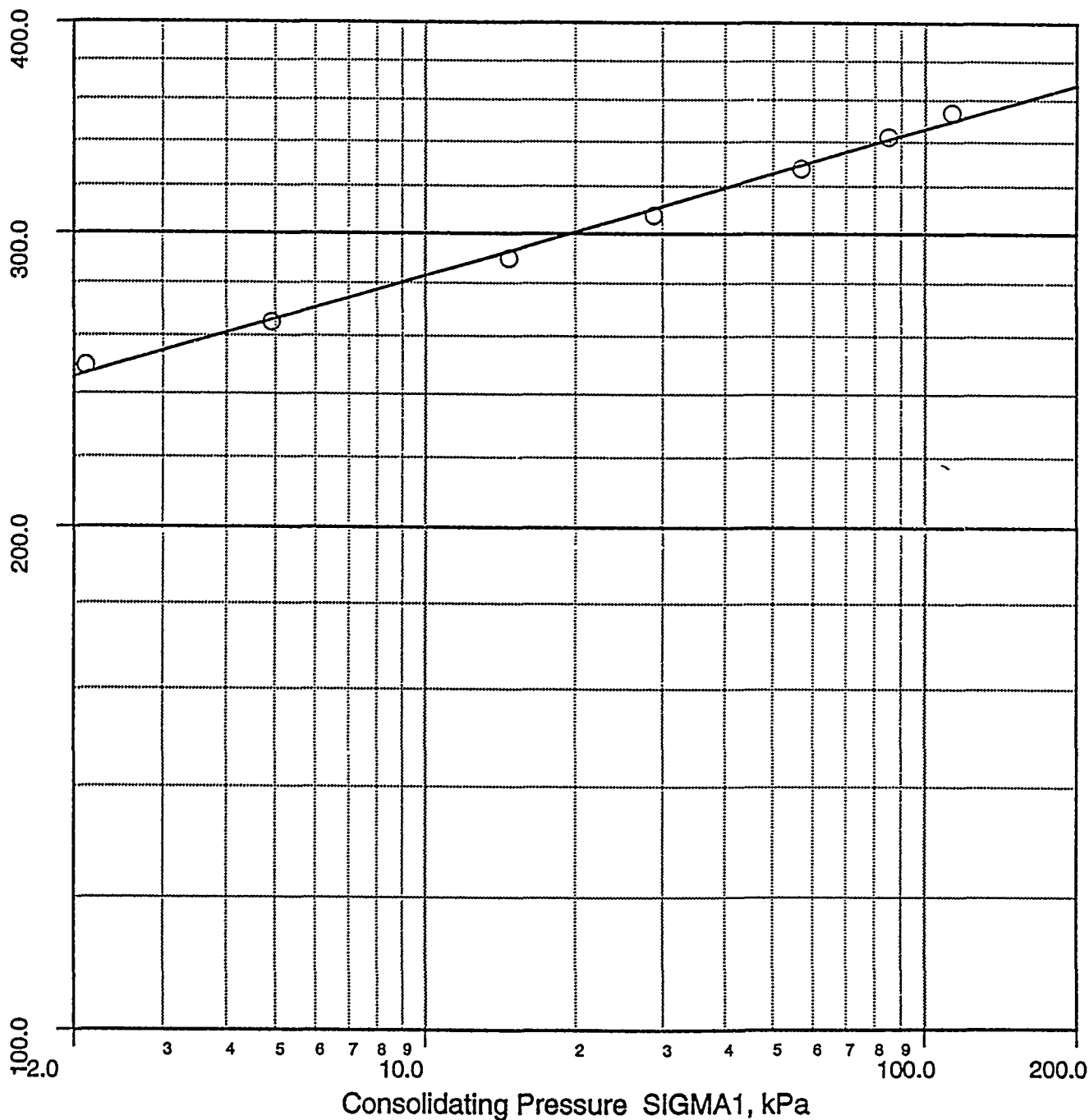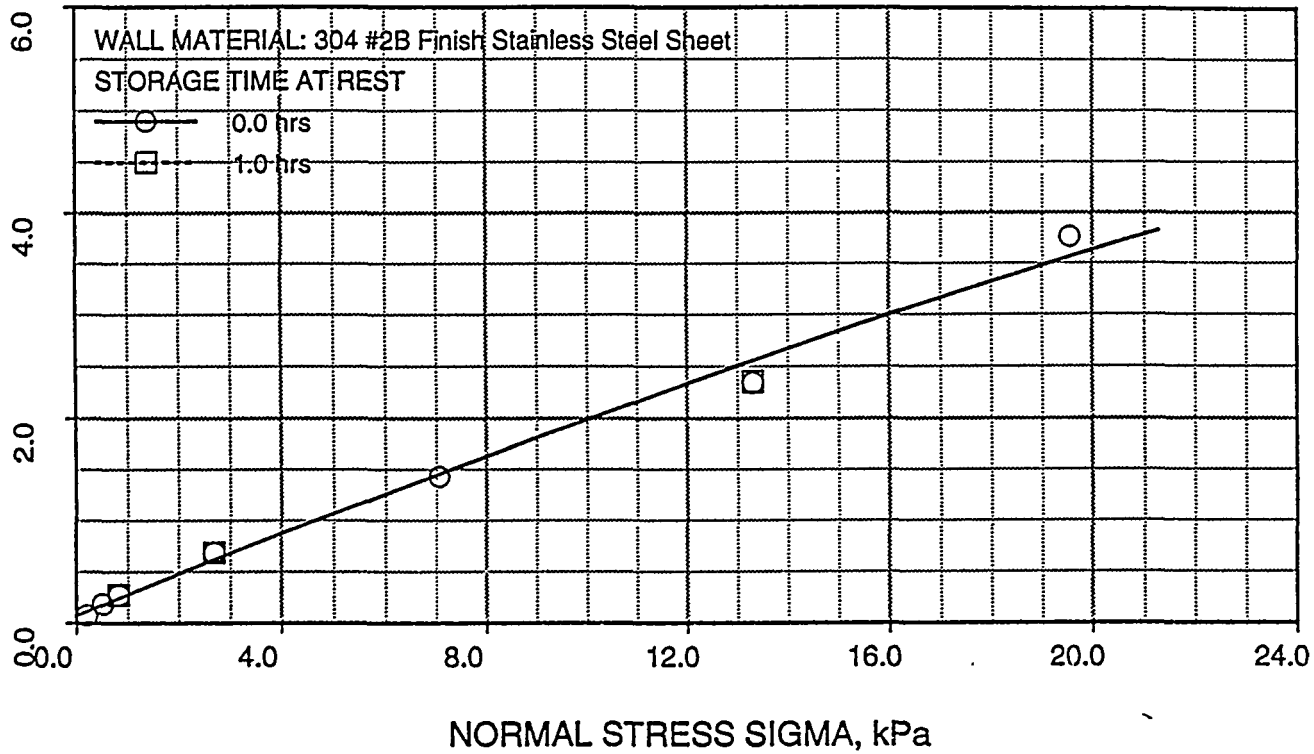
JOB#: 932931
ID#: 18778

YIELD LOCUS

⊙	Steady State	
□	.0 hrs 140 deg C	
△	1.0 hrs 140 deg C	

V1	5.9 kPa
Fc inst	1.7 kPa
Fc 1. hrs	2.7 kPa
Delta	71.6 deg
Phi	68.2 deg

Normal Load V, N for 6.35 cm cell

BULK MATERIAL: WOOD DUST
PARTICLE SIZE: As Rec'd
MOISTURE % WT: As Rec'd(7.24%)

CREATE: 93/12/16   JOB#: 932931
RUN: 93/12/20   ID#: 18778

YIELD LOCUS

Legend and plotted data within chart:
- ⊙ Steady State
- □ 0 hrs 140 deg C
- △ 1.0 hrs 140 deg C

V1	11.8 kPa
Fc inst	3.3 kPa
Fc 1. hrs	4.8 kPa
Delta	70.1 deg
Phi	66.7 deg

Y-axis values: 48.0, 40.0, 32.0, 24.0, 16.0, 8.0, 0.0

X-axis values: 0.0, 8.0, 16.0, 24.0, 32.0, 40.0, 48.0

Normal Load V, N for 6.35 cm cell

BULK MATERIAL: WOOD DUST
PARTICLE SIZE: As Rec'd
MOISTURE % WT: As Rec'd(7.24%)

CREATE: 93/12/16   JOB#: 932931
RUN: 93/12/20   ID#: 18778

YIELD LOCUS

		V1	23.8 kPa
Steady State		Fc inst	6.8 kPa
.0 hrs 140 deg C		Fc 1. hrs	9.0 kPa
1.0 hrs 140 deg C		Delta	64.5 deg
		Phi	60.1 deg

Normal Load V, N for 6.35 cm cell

BULK MATERIAL: WOOD DUST
PARTICLE SIZE: As Rec'd
MOISTURE % WT: As Rec'd(7.24%)
TEMPERATURE: 140 deg C

CREATE: 93/12/16   JOB#: 932931
RUN: 93/12/20   ID#: 18778

BULK DENSITY VS. CONSOLIDATING PRESSURE

Consolidating Pressure SIGMA1, kPa

BULK MATERIAL: WOOD DUST
PARTICLE SIZE: As Rec'd
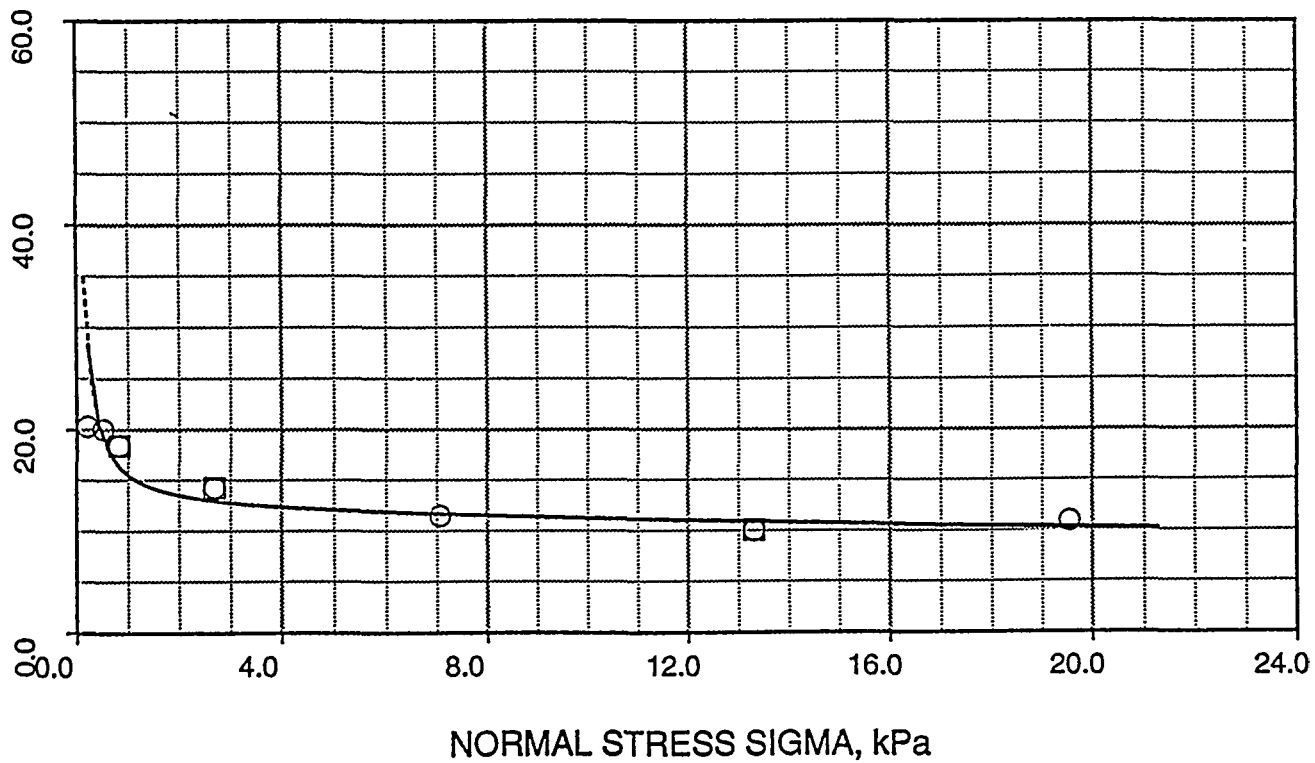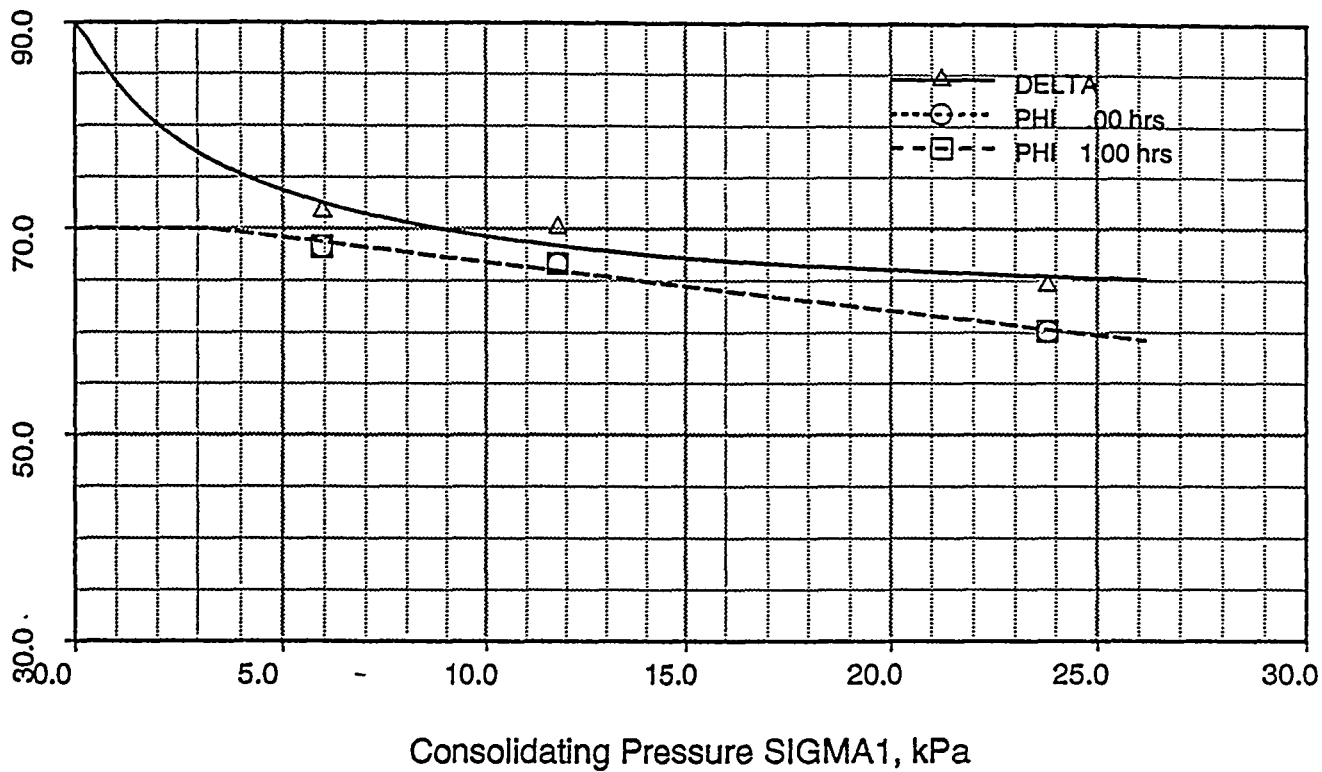MOISTURE % WT: As Rec'd(7.24%)
TEMPERATURE: 140 deg C

CREATE: 93/12/16   JOB#: 932931
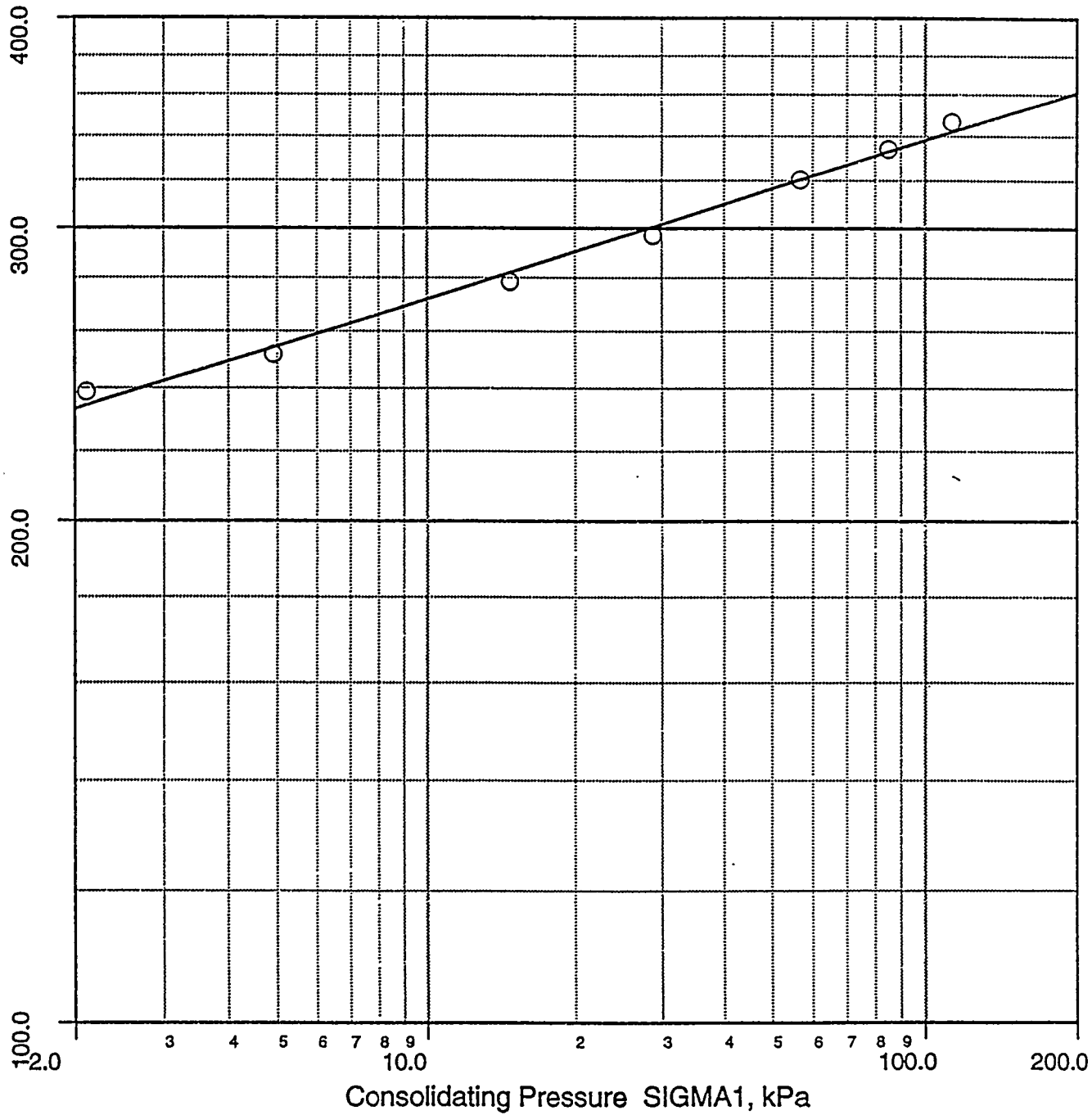RUN: 93/12/21   ID#: 18778

WALL YIELD LOCUS

WALL MATERIAL: 304 #2B Finish Stainless Steel Sheet
STORAGE TIME AT REST
  ○——— 0.0 hrs
  □······ 1.0 hrs

NORMAL STRESS SIGMA, kPa

WALL FRICTION ANGLE

NORMAL STRESS SIGMA, kPa
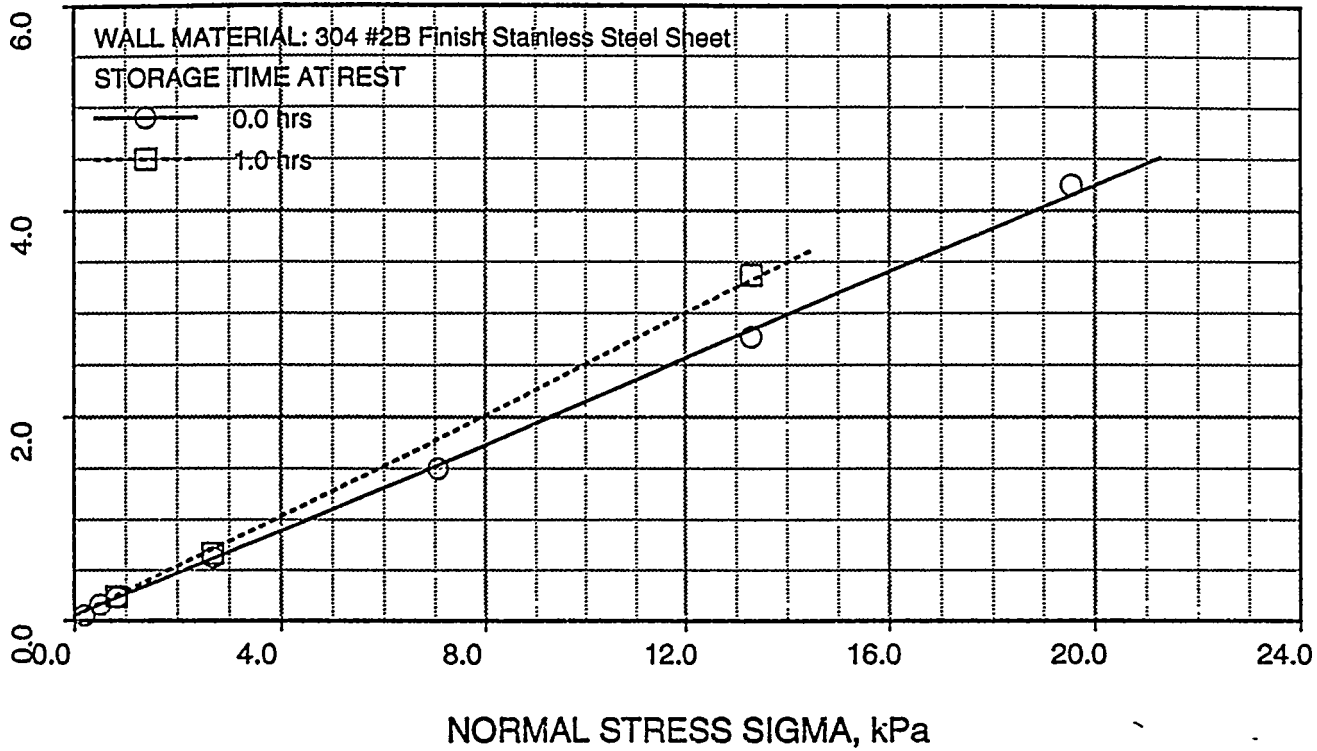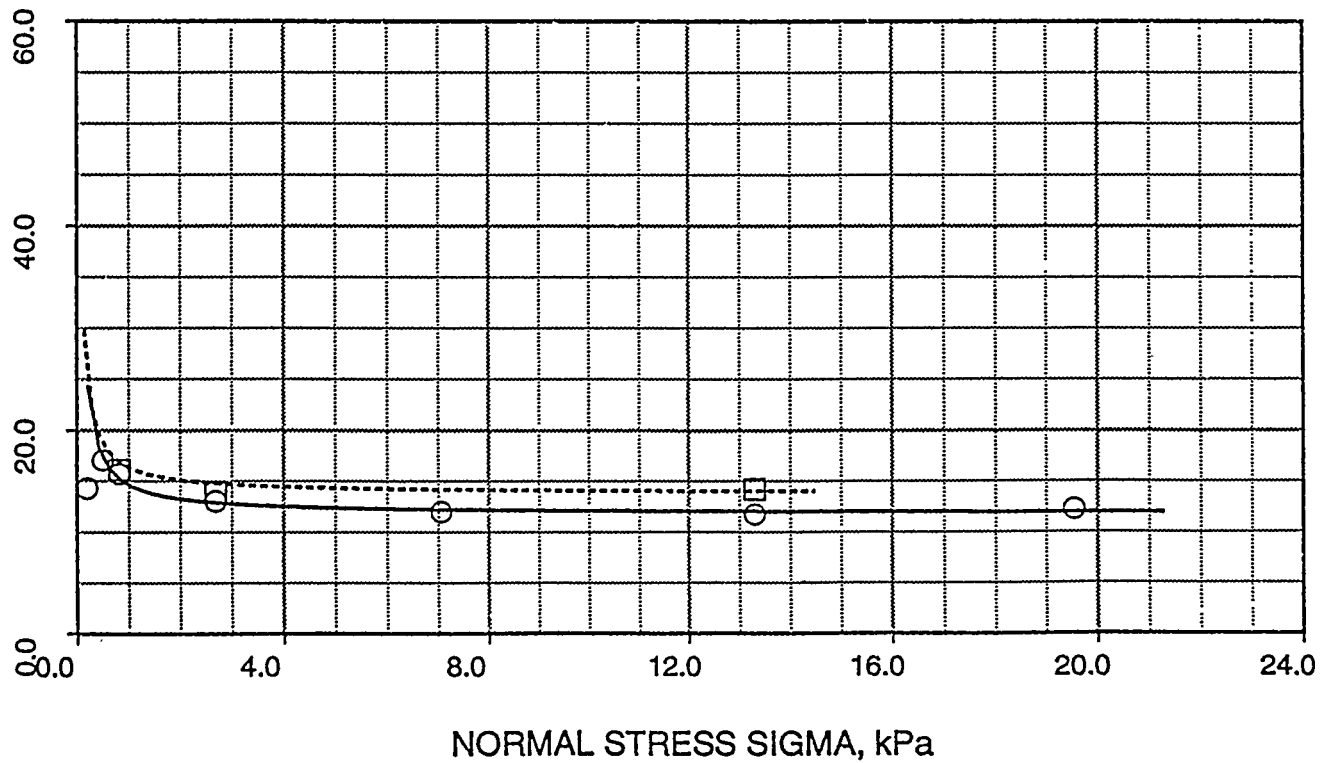
. angle of inter. friction = 43.13

jle of wall friction (PHIW) = 17.90   *STAINLESS STEEL*

эta   = 27.00

эw factor   =   1.42

HOPPER DESIGN - FLOW FUNCTION

TITLE = COAL(CRE)0h at rest

Low factor   =   1.42
all slope (degrees) =   27.00
ılk density (SI units) = 910.90
alue of CAS   =   0.50
Lameter of aperture =   0.13

CONICAL HOPPER DESIGN

TITLE = COAL(CRE)0h at rest
Wall slope (degrees)   =   27.00
Bulk density (SI units)   =   910.90
Weight capacity in tonnes   =   20.00
Angle of repose   =   24.90

MIN OUTLET DIAM	CYL-INDER DIAM	CONE HEIGHT	CYL-INDER HEIGHT	TOTAL HEIGHT	REF
0.13	1.00	0.85	27.82	28.67	1
0.13	1.50	1.34	12.20	13.54	2
0.13	2.00	1.83	6.68	8.51	3
0.13	2.50	2.32	4.07	6.40	4
0.13	3.00	2.81	2.62	5.43	5
0.13	3.50	3.30	1.71	5.01	6
0.13	4.00	3.79	1.09	4.88	7

SEMI-INCLUDED ANGLE OF CONE =   27.00 DEGREES

f. angle of inter. friction = 42.75

gle of wall friction (PHIW) = 17.90 *STAINLESS STEEL*

eta   = 27.00

ow factor   = 1.42

HOPPER DESIGN - FLOW FUNCTION

TITLE = COAL(CRE)1h at rest

low factor   =   1.42
all slope (degrees) =   27.00
1lk density (SI units) =   910.90
alue of CAS   =   1.48
iameter of aperture =   0.40

CONICAL HOPPER DESIGN

TITLE = COAL(CRE)1h at rest
Wall slope (degrees)   =   27.00
Bulk density (SI units)   =   910.90
Weight capacity in tonnes =   20.00
Angle of repose   =   24.90

MIN OUTLET DIAM	CYL-INDER DIAM	CONE HEIGHT	CYL-INDER HEIGHT	TOTAL HEIGHT	REF
0.40	1.00	0.59	27.88	28.48	1
0.40	1.50	1.08	12.26	13.35	2
0.40	2.00	1.57	6.74	8.32	3
0.40	2.50	2.06	4.14	6.20	4
0.40	3.00	2.56	2.69	5.24	5
0.40	3.50	3.05	1.78	4.82	6
0.40	4.00	3.54	1.15	4.69	7

SEMI-INCLUDED ANGLE OF CONE =   27.00 DEGREES

f. angle of inter. friction = 42.86

gle of wall friction (PHIW) = 12.10   *STAINLESS STEEL*

eta   = 34.00

ow factor   =   1.46

HOPPER DESIGN - FLOW FUNCTION

TITLE = Forest residue (Oh)

low factor   =   1.46
all slope (degrees) =   34.00
ulk density (SI units) =   273.80
alue of CAS   =   0.75
iameter of aperture =   0.69

CONICAL HOPPER DESIGN

TITLE = Forest residue (Oh)

Wall slope (degrees)   =   34.00
Bulk density (SI units)   =   273.80
Weight capacity in tonnes   =   6.00
Angle of repose   =   34.60

MIN OUTLET DIAM	CYL- INDER DIAM	CONE HEIGHT	CYL- INDER HEIGHT	TOTAL HEIGHT	REF
0.69	1.00	0.23	28.01	28.24	1
0.69	1.50	0.60	12.48	13.08	2
0.69	2.00	0.97	7.04	8.01	3
0.69	2.50	1.34	4.52	5.86	4
0.69	3.00	1.71	3.15	4.86	5
0.69	3.50	2.08	2.31	4.40	6
0.69	4.00	2.45	1.77	4.22	7

SEMI-INCLUDED ANGLE OF CONE =   34.00 DEGREES

. angle of inter. friction = 42.86

le of wall friction (PHIW) = 28.00   *RUSTY STEEL*

ta   = 13.00

w factor   =   1.33

HOPPER DESIGN - FLOW FUNCTION

TITLE = Forest residue (0h)

ow factor   =   1.33
ll slope (degrees)   =   13.00
lk density (SI units) =   273.80
lue of CAS   =   0.74
ameter of aperture   =   0.61

CONICAL HOPPER DESIGN

TITLE = Forest residue (0h)
Wall slope (degrees)   =   13.00
Bulk density (SI units)   =   273.80
Weight capacity in tonnes =   6.00
Angle of repose   =   34.60

MIN OUTLET DIAM	CYL-INDER DIAM	CONE HEIGHT	CYL-INDER HEIGHT	TOTAL HEIGHT	REF
0.61	1.00	0.85	27.83	28.69	1
0.61	1.50	1.94	12.08	14.02	2
0.61	2.00	3.02	6.41	9.43	3
0.61	2.50	4.10	3.65	7.75	4
0.61	3.00	5.19	2.04	7.22	5

SEMI-INCLUDED ANGLE OF CONE =   13.00 DEGREES

f. angle of inter. friction = 42.52

gle of wall friction (PHIW) = 16.99

eta   = 28.00

ow factor   = 1.43

HOPPER DESIGN - FLOW FUNCTION

TITLE = COAL(CRE) 0h at rest   MC.4.19% d50=0.95mm Stainless Steel

low factor   =   1.43
all slope (degrees) =   28.00
ulk density (SI units) =   910.90
alue of CAS   =   1.27
iameter of aperture =   0.34
CONICAL HOPPER DESIGN

TITLE =
AL(CRE) 0h at rest   MC.4.19% d50=0.95mm Stainless Steel
Wall slope (degrees)   =   28.00
Bulk density (SI units) =   910.90
Weight capacity in tonnes =   20.00
Angle of repose   =   40.30

MIN OUTLET DIAM	CYL-INDER DIAM	CONE HEIGHT	CYL-INDER HEIGHT	TOTAL HEIGHT	REF
0.34	1.00	0.62	28.00	28.63	1
0.34	1.50	1.09	12.46	13.55	2
0.34	2.00	1.56	7.00	8.57	3
0.34	2.50	2.03	4.47	6.50	4
0.34	3.00	2.50	3.09	5.59	5
0.34	3.50	2.97	2.25	5.22	6
0.34	4.00	3.44	1.70	5.14	7

SEMI-INCLUDED ANGLE OF CONE =   28.00 DEGREES

'. angle of inter. friction =   43.30

[le of wall friction (PHIW) =   17.52

;ta   =   27.00

)w factor   =   1.41

HOPPER DESIGN - FLOW FUNCTION

TITLE = COAL(CRE) 0h at rest   MC.6.59% d50=0.95mm Stainless Steel

,ow factor   =   1.41
[ll slope (degrees)   =   27.00
[lk density (SI units)   =   910.90
[lue of CAS   =   0.50
,ameter of aperture   =   0.13

CONICAL HOPPER DESIGN

TITLE =
[L(CRE) 0h at rest   MC.6.59% d50=0.95mm Stainless Steel

Wall slope (degrees)	=	27.00	
Bulk density (SI units)	=	910.90	
Weight capacity in tonnes	=	20.00	
Angle of repose	=	32.20	

MIN OUTLET DIAM	CYL-INDER DIAM	CONE HEIGHT	CYL-INDER HEIGHT	TOTAL HEIGHT	REF
0.13	1.00	0.85	27.87	28.72	1
0.13	1.50	1.34	12.28	13.62	2
0.13	2.00	1.83	6.79	8.62	3
0.13	2.50	2.32	4.21	6.53	4
0.13	3.00	2.81	2.79	5.60	5
0.13	3.50	3.30	1.90	5.21	6
0.13	4.00	3.79	1.31	5.11	7

SEMI-INCLUDED ANGLE OF CONE =   27.00 DEGREES

f. angle of inter. friction = 42.30

gle of wall friction (PHIW) = 19.87

eta   = 25.00

ow factor   = 1.43

HOPPER DESIGN - FLOW FUNCTION

TITLE = COAL(CRE) 1h at rest   MC.6.59% d50=0.95mm Stainless Steel

low factor   =   1.43
all slope (degrees) =   25.00
ulk density (SI units) =   910.90
alue of CAS   =   0.50
iameter of aperture =   0.13

CONICAL HOPPER DESIGN

TITLE =
AL(CRE) 1h at rest   MC.6.59% d50=0.95mm Stainless Steel

Wall slope (degrees)   =   25.00
Bulk density (SI units)   =   910.90
Weight capacity in tonnes =   20.00
Angle of repose   =   32.20

MIN OUTLET DIAM	CYL- INDER DIAM	CONE HEIGHT	CYL- INDER HEIGHT	TOTAL HEIGHT	REF
0.13	1.00	0.93	27.85	28.78	1
0.13	1.50	1.47	12.24	13.71	2
0.13	2.00	2.00	6.73	8.73	3
0.13	2.50	2.54	4.14	6.68	4
0.13	3.00	3.08	2.70	5.78	5
0.13	3.50	3.61	1.80	5.41	6

SEMI-INCLUDED ANGLE OF CONE =   25.00 DEGREES

f. angle of inter. friction = 45.80

yle of wall friction (PHIW) = 14:01

eta   = 31.00

ow factor   = 1.40

HOPPER DESIGN - FLOW FUNCTION

TITLE = COAL(CRE) 0h at rest   MC.11.94% d50=0.95mm Stainless Steel

low factor   =   1.40
all slope (degrees) =   31.00
ilk density (SI units) =   910.90
alue of CAS   =   2.90
iameter of aperture =   0.79

CONICAL HOPPER DESIGN

TITLE =
AL(CRE) 0h at rest   MC.11.94% d50=0.95mm Stainless Steel

Wall slope (degrees)   =   31.00
Bulk density (SI units)   =   910.90
Weight capacity in tonnes =   20.00
Angle of repose   =   28.30

MIN OUTLET DIAM	CYL-INDER DIAM	CONE HEIGHT	CYL-INDER HEIGHT	TOTAL HEIGHT	REF
0.79	1.00	0.17	28.05	28.22	1
0.79	1.50	0.59	12.44	13.03	2
0.79	2.00	1.00	6.95	7.95	3
0.79	2.50	1.42	4.38	5.80	4
0.79	3.00	1.84	2.96	4.80	5
0.79	3.50	2.25	2.08	4.34	6
0.79	4.00	2.67	1.50	4.17	7

SEMI-INCLUDED ANGLE OF CONE =   31.00 DEGREES

FLOWTECHNICAL CHARACTERISTICS OF FUELS

GENERAL

General flow-technical characteristics can be used for comparing flowability, flow, feed-conveying and storage characteristics for different bulk materials. Laboratory evaluations of this kind make it possible to score characteristics determined for different bulk materials. Flow-technical characteristics required for these evaluations are introduced below.

ANGLE OF REPOSE

The angle of repose is formed between the horizontal level and the slope of the cone-shaped material heap, if the material falls freely and at a constant speed from a small height.

The angle of repose was determined for milled peat and sawdust with equipment of Féderation Européenne de la Manutention (FEM) shown in Figure 1. The material was poured into the vessel at a constant speed and from a certain height from the bottom of the vessel, and it flew through the bottom opening on a horizontal level. The angle between the material slope and the level α was measured at three points of the heap (at 90° distances). The angle of repose is the mean of these measurements.
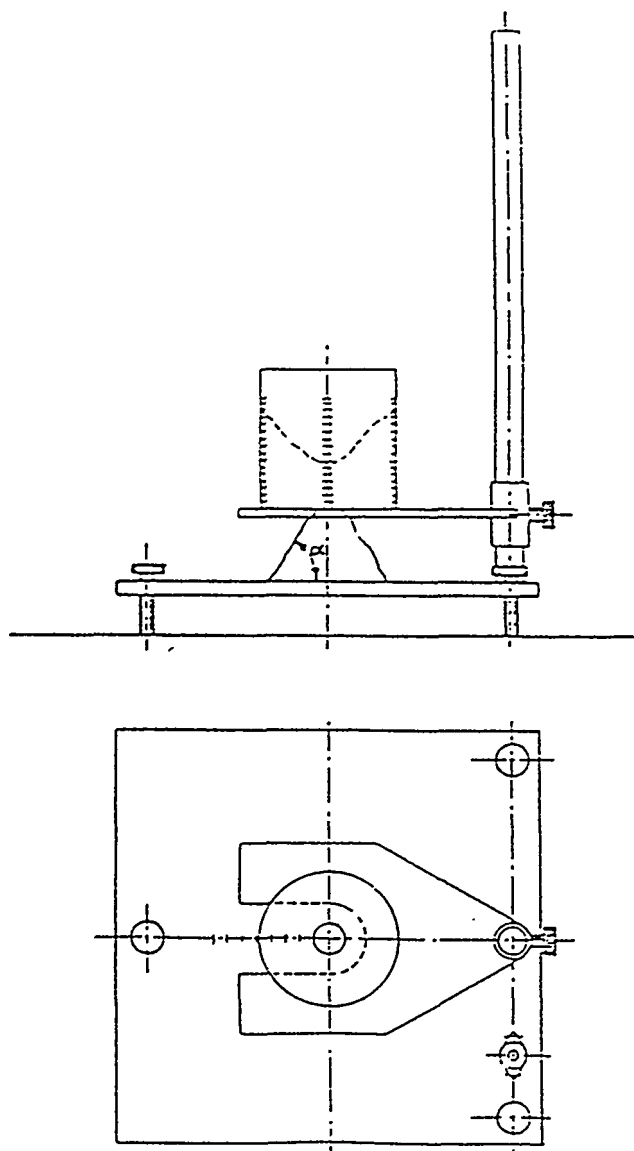
Figure 1. Equipment for the determination of the angle of repose.

ANGLE OF FLOW

The angle of flow is the angle formed, for example, between the bulk material and the horizontal level, when a "supported" material lot is allowed to discharge.

The determination was carried out for a sample of 500 cm^3 with equipment shown in Figure 2. The sample was poured at a standard speed onto the middle of the vessel, the

bottom opening of the vessel being closed. The pouring height of the material was also kept the same over the test.
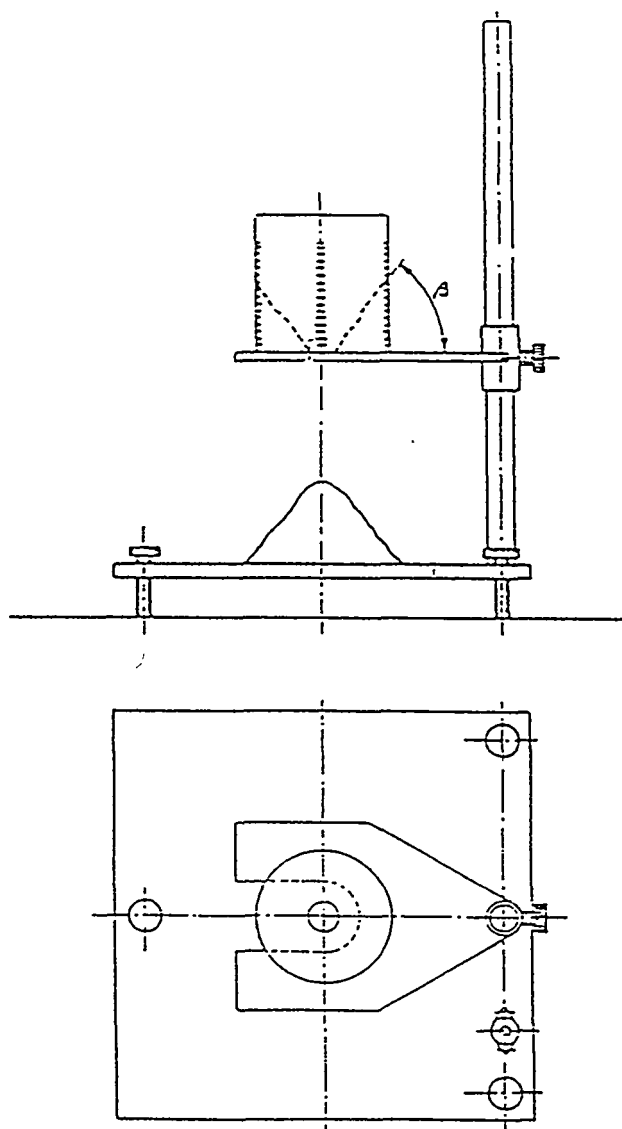

Figure 2. Equipment for the determination of the angle of flow (Féderation Européenne de la Manutention, Working Group 4, Pneumatic Handling, Agenda. 4th October 1983, Paris.

Material was poured until it overflowed the vessel edge, and the excess material was then swept off. The material was allowed to stabilize for 15 min, the bottom plate was then opened and the material was allowed to flow freely from a certain height onto the bottom level.

As soon as the flow stopped, the slopes of the "crater" formed in the vessel were measured at 90° distances, and the mean angle of flow was calculated from these measuring values.

BULK DENSITY

In this connection, the bulk density means the mass of the bulk material for a volume unit and its value is dependent on the setting of the material and on the amount of air contained in the material. The bulk density is given as SI units, kg/dm^3 or kg/m^3.

The bulk density was determined with equipment shown in Figure 3, also using a vibrator and a standard feeder. Two different vessel sizes, 500 cm^3 (FEM volume) and 1 000 cm^3 in nominal volume, were used to compare the effect of the vessel size on the values of bulk density. The exact volume of the vessels was determined during the measurement with water (+20 °C). The empty vessel was weighed exactly (±10 mg).

After volume measuring the vessel was laid on the plate below the pouring funnel. The bottom opening of the funnel was 150 mm above the upper edge of the vessel. The material was fed at a speed of 40 cm^3/min in the middle of the funnel from the height of 40 mm from the upper edge of the funnel. Feeding was continued until it overflow the edge of the vessel, and the excess material was then swept off. After weighing the vessel was vibrated by dropping it from the height of 3 mm on the plate 1 000 ± 50 times, and the bulk volume of the material in the vessel was recorded. If the reduction from the former reading was more than 5 cm^3 the vibration was repeated until the difference of two successive readings was less than 5 cm^3. The bulk density of the material was calculated on the basis of this last reading.
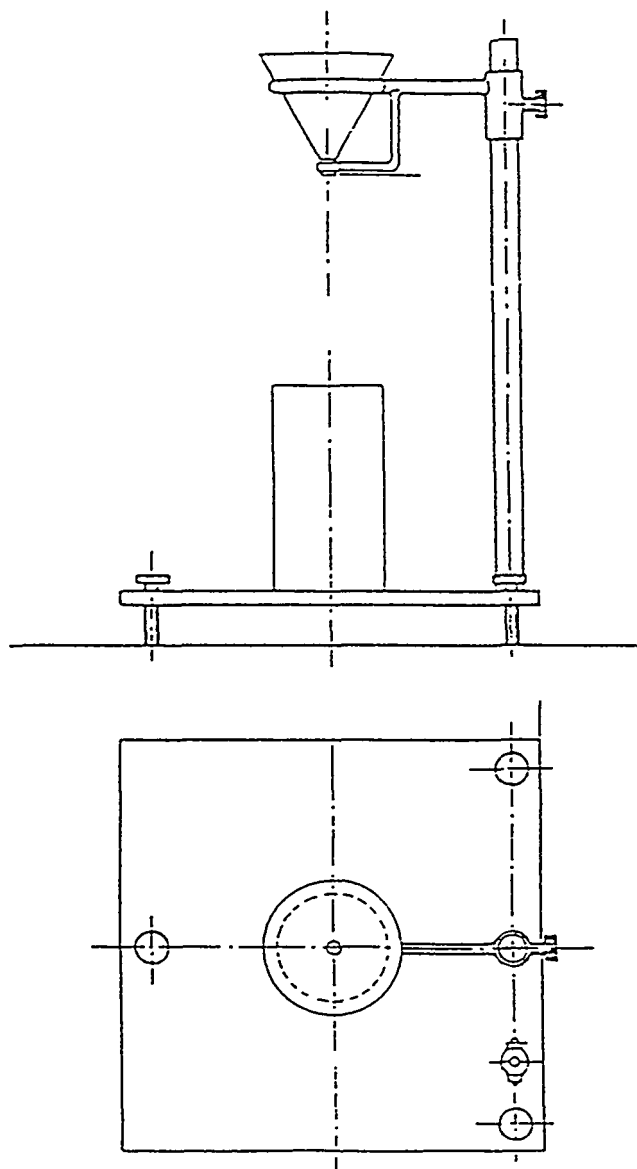
Figure 3. Equipment for measuring bulk density (Féderation Européenne de la Manutention, Working Group 4, Pneumatic Handling, Agenda. 4th October 1983, Paris).

FRICTION COEFFICIENTS

Various friction coefficients were determined for milled peat and sawdust with equipment shown in Figure 4. It was possible to change plates of different materials and coatings in the equipment.

The determination was started by laying the plate in a horizontal position. Then a certain amount of material was poured on the plate. The plate was inclined at a constant speed until the material started sliding, when the inclining was stopped immediately. The angle of slide obtained was measured. The corresponding friction coefficient was calculated from this angle of slide.
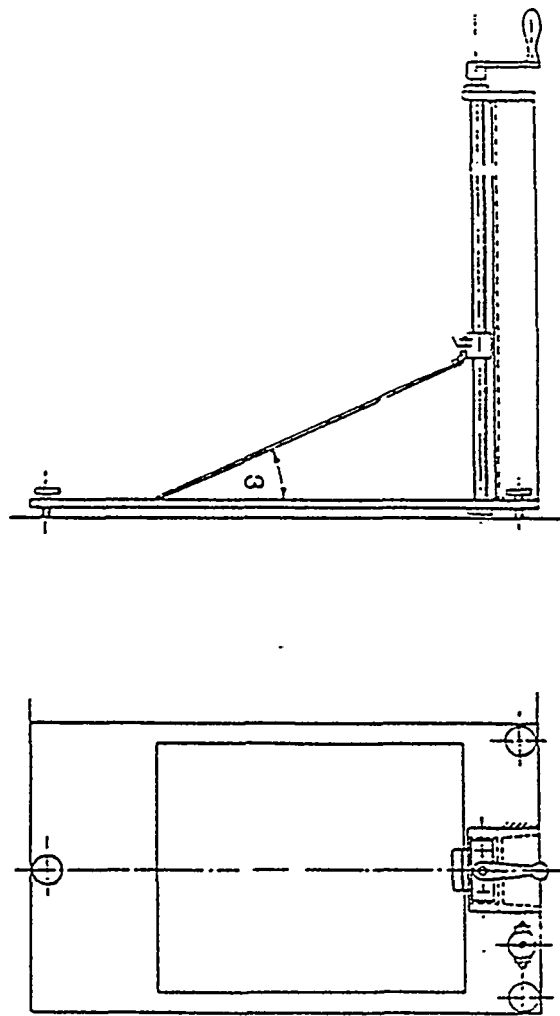
Figure 4. Equipment for the determination of the angle of slide (fine materials)in (Féderation Européenne de la Manutention, Working Group 4, Pneumatic Handling, Agenda. 4th October 1983, Paris).