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UNIVERSITY OF ALBERTA

THE DURABILITY OF SELECTED GEOTEXTILE FABRICS TO HEAVY OIL WELL FLUIDS

BY

CYNTHIA H. PENNER ©

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH IN
PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE
IN THE
DEPARTMENT OF
CLOTHING AND TEXTILES

EDMONTON, ALBERTA
FALL 1990

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DEGREE: MASTER OF SCIENCE

YEAR THIS DEGREE GRANTED: 1990

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ABSTRACT

The Durability of Selected Geotextile Fabrics to Heavy Oil Well Fluids

The heavy oil industry requires a well filter that will allow flow of oil while retaining the formation sand. Also, the filter must remain durable over an extended time. The objective of this study was to determine the effects of exposure to fluids from a heavy oil well on the mechanical and physical properties of selected geotextile filter fabrics. In a laboratory study, specimens from two polyester and one polypropylene nonwoven geotextiles were immersed in heavy oil and produced water for periods of 0, 15, 30, 60 and 120 days. Analysis of variance statistical tests were used to compare fibre diameter measurements at 0, 15 and 120 days and to compare burst strength test results after 0, 30, 60 and 120 days. The Scanning Electron Microscope (SEM) was used to observe qualitative changes in the surface appearance and cross sections of the fibres. Electron Dispersive X-ray Anaylsis (EDXA) was completed on the fibres that showed the greatest change in appearance. Statistical analysis indicated that the fibre diameter and burst strength of the polyester fabrics was not significantly different ($\alpha = 0.1$) after immersion in the oil well fluids, whereas, the fibre diameter and burst strength of the polypropylene fabric was significantly different after immersion in the well fluids. SEM indicated that the polypropylene fibres had localized swelling along the fibre axis after immersion in the heavy oil. EDXA indicated that compounds present in oil were also present in the cross section of the polypropylene fabric. It was concluded that polyester nonwoven fabrics were durable to oil well fluids. Polyester nonwoven goetextiles are relatively inexpensive to produce therefore, it is suggested that the permeability of the fabric may be adjusted by specifiying to the manufacturer opening size criteria for the development of an oil well filter. It is recommended that further research be conducted to determine the combined effect of well fluids, heavy oil and produced water, on the durability of polyester nonwoven fabrics.

ACKNOWLEDGEMENTS

There have been many people who have inspired, encouraged, supported and constructively critized my work while I progressed through my master of science program. I would like to express my gratitude to them.

The past two years have been a great learning experience. I would like to thank Dr. Nancy Kerr for teaching me to be thorough in the laboratory as well as when I am writing. Her editorial suggestions were always appreciated. I would like to thank Ms Elizabeth Richards for sharing her knowledge about geosynthetics with me.

One of the most challenging aspects of my program was learning to apply textile science to engineering applications. I would like to thank Dr. J.D. Scott for teaching me and inspiring me to learn the technical engineering aspects of the overall oil well filtration project.

I would also like to thank Dr. Nelma Fetterman, who sat on my committee for the majority of my master's program. Her expertise in statistics and research methods enhanced my research skills. I would also like to thank Dr. Betty Crown for her continual interest in research and agreeing to be on my committee late in my program. Her expertise in conducting research was appreciated.

I would like to extend my sincere gratitude to Ms. Sherri Martin-Scott. Her expertise made a significant contribution to my research. The long conversations about the implications of geosynthetic applications, the research process and her personal support were always appreciated.

I would like to thank the people who provided technical support: Sam Proskin (geotechnical engineer), George Braybrook (SEM lab) and Gunnar Bloggett (graphics expert). Their professional expertise helped me carry out my project efficiently.

Part of my graduate experience was my involvement with the Graduate Students Association. I would like to thank all the people who enhanced my life through this organization. In particular, I would like to thank Mary and Scott Meister for ensuring I had a life.

I could list many friends who also contributed to my well-being during my master's program but there are too many to name individually. I would like to thank my friends across the country who made numerable long-distance support phone calls, the Clothing and Textile grad students who always understood the need for a social life, the Geology gang who were always ready to have fun, the summer students who assisted me with my research and my 'special new friend' Janok who inspired me to finish my thesis.

Last but not least, I would like to thank Imperial Esso and the Alberta Oil Sands Technology Research Authority for funding my master's research. Without their financial assistance this project would have been impossible .

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CHAPTER 1 INTRODUCTION

Background

The focus of this study was to determine the long term durability of selected nonwoven geotextiles to fluids produced from heavy oil wells. A three year research program was conducted by the Departments of Clothing and Textiles and Civil Engineering at the University of Alberta to examine the use of geotextile filters to control the flow of formation sand into heavy oil wells. The program included a feasibility study and extensive laboratory testing (Kerr, Richards, Scott, & Martin-Scott 1988). Kerr, Scott, Richards and Martin-Scott (1990) investigated the filtration and permeability properties of selected nonwoven geotextile fabrics. Based on data from preliminary filtration testing three fabrics were selected for further filtration and permeability tests (Wong, personnal communication, 1989). In addition to filtration, it is equally important that the geotextile remain durable in the well for an extended period of time. In this study, these fabrics were immersed in heavy oil and produced water for periods of 0, 15, 30, 60, 120 days, then tested for changes in fibre diameter and burst strength to determine the durability of geotextiles to well fluids.

The term geotextile, coined by J.P. Giroud, refers to any permeable synthetic material used with foundations, soils, rock, earth or any other geotechnical engineering related material that is an integral part of an engineering project, structure or system. Geotextiles are used mainly in separation, reinforcement and filtration applications. The nonwoven fabric structure is the most common, with 60 % of the geotextile market share (Jagielski, 1990). The use of a geotextile filter for a heavy oil well is a new and innovative application.

During the oil recovery process, oil, water and sand are brought to the surface of the earth. The sand may cause the perforated oil well casing to corrode or become plugged, causing inefficient production. The sand, which contains toxic chemicals, is brought to the surface and becomes a hazardous waste. Disposal of the waste contributes to the current environmental problems of the oil industry. A method of oil recovery which would reduce the amount of sand brought to the surface would benefit the industry, by lowering costs and creating less environmental damage.

The purpose of this study is to determine the physical and mechanical properties of geotextiles after being immersed in heavy oil well fluids for an extended time. In this research typical heavy oil well fluids from a well in the Lloydminster, Alberta region are used.

Description of Lloydminster Area

When developing a new type of filter for heavy oil wells the geology of the region must be considered. Each oil deposit has unique geological and chemical characteristics that must be considered when developing an oil recovery method. The area of study is the Lloydminster, Alberta region (Figure 1).

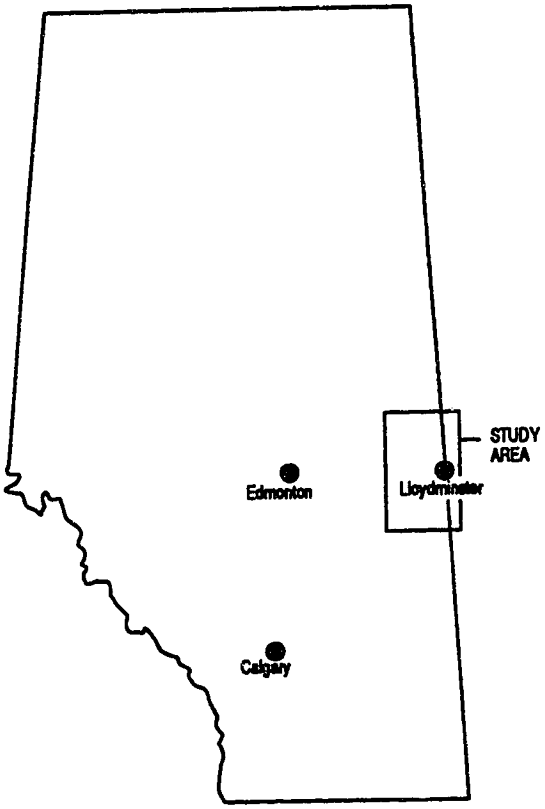


Figure 1 Geographic Location of the Study Area

The Lloydminster area spans the provincial boundary between Saskatchewan and Alberta, 370 to 500 km north of the border between Canada and the United States. The area is 52° 20' and 53° 30' N latitude and 109° and 111° W longititude. The Canada land survey system defines the Lloydminster area as township 39 to 52, range 21W 3d meridian to range 7W 4th meridian (Vigrass, 1977) . Many geological studies have been conducted in this area in order to determine the location of oil deposits and to identify the formation conditions. The estimated oil in place is 3 billion barrels (500 million m^3), of which only 8.1% is recoverable in oil wells by conventional methods. Aside from the problems of sand plugging the well, the rate of recovery is low because the oil is very viscous, the formation water is more mobile than the oil and there is little gas available in solution. The viscosity of heavy oil ranges from 100 to 100,000 MPa sec at ambient reservoir temperature (Vigrass, 1977). The oil has a density of 10 to 25° American Petroleum Institute (API) units or 934 to 1000 Kg/m^3. As the density of the oil increases, API units decrease. The relationship between the API unit and specific gravity of water at 60^0 C is:

$$SG_{60} = \frac{141.5}{^{o}API + 131.5}$$

(Burcik, 1979)

Sand Production

A typical well completion is shown in Figure 2. A steel pipe is cemented into the well bore. Perforations are made through the pipe and cement casing into the oil formation. Oil is pumped to the surface through the perforations.

One of the main problems encountered in most Lloydminster area heavy oil wells is that sand is pumped into the well, through the perforations along with the heavy oil and water from the formation. The Lloydminster area heavy oil fields are characterized by uncemented angular sand grains. Sand failure, the movement of the sand in the reservoir, may be due to non-uniform lateral loading, high axial compressive loading because of failure of the overlying casing adjacent to the perforated pipe or due to large chunks of sand entering perforations in the pipe completion causing erosion of the perforations or openings. Frequently, some of the perforations become plugged, and as a result, the velocity of flow through the remainder of the openings increases, and the abrasive sand erodes the perforations. Often the sand production is so high that well workover costs are $200,000 for each year that a well is productive (Baycroft, 1980). Workovers may be needed as early as 13 days after oil recovery has begun.

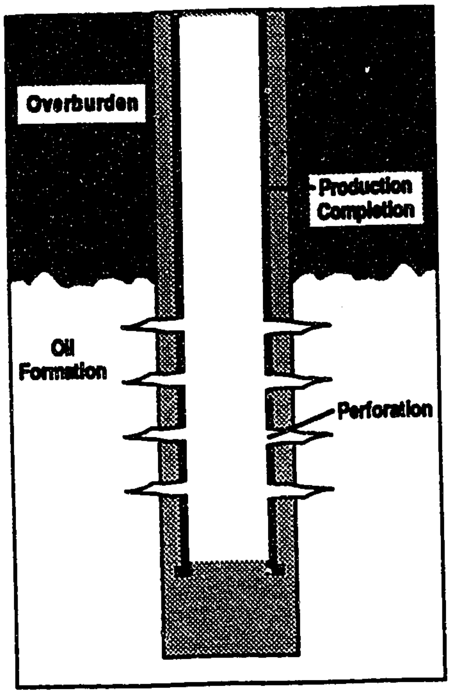


Figure 2 Typical Oil Well Completion

Hodgson and Baker (1959) indicated that variations in sand grain size, layer composition and deposit depth exist within Lloydminster heavy oil wells. Layers of sediments were deposited over time to form the cretaceous units that are present. The majority of the deposits are found within the Mannville Group which can be dividied into three subsections: upper, middle and lower. These subsections are further devided into units, which exhibit distinct characteristics. Each section has unique characteristics that must be considered when developing oil recovery methods. Smith (1985), Bratli and Risnes (1981) and Hall and Harrisberger (1970) investigated sand production and oil production rates and determined that instability in the reservoir can be expected to occur at the current production rates.

Loose sand surrounding the well reduces the production and profitability of a well. The production of heavy oil in the Lloydminster area has become a complicated process of trying to increase efficiency rates while trying to solve the problems associated with loose sand production.

Sand Control

A perforated casing is the most common filter in the oil industry simply because it is adaptable to a variety of situations; however, it is not a sand control device on its own. The percentage of open area in the casing is low, creating high entrance velocities which are undesirable for sand control.

Various methods have been used in heavy oil wells to control sand production. Patton and Abbott (1981) indicate three methods of sand control: (1) mechanical bridging of sand through the use of screens, liners and gravel packs, (2) stabilizing sand by creating natural arches and (3) sand consolidation.

Livesay and Toma (1983) discussed the development of the stainless steel "wool" filter. The advantage of this filter is that it is chemically and mechanically stable. The steel wool is confined between two layers of wire mesh. The wire mesh cloth provides a mechanism to aid in sand bridging. The steel wool is a porous structure that allows the oil to pass through while retaining the sand. This filter works in both ambient and high temperature wells, although it will corrode in the alkaline conditions present in some heavy oil wells.

Slotted liners and screens have shown little success in sand control (Patton & Abbott, 1981; Suman,1975). Once the screens or liners become plugged, it is virtually impossible to clean them out. Prepacked liners, with integral gravel packs, can be successful if they are designed for a specfic oil well.

These sand control methods have been partially successful, however, low production rates are still a common problem. The design of a new well filter that would successfully control sand production and maintain production rates is a current need in the oil industry. The use of geotextiles for water well filtration has provided a basis for other filtration applications. Lyness, Devenny and Dabrowski (1987) examined the similarities between water well completions and oil well completions. They found that well design and well development were similar in both situations. Well design is the most important aspect of a well's performance.

Kerr et al (1988) in their feasibility study discussed the possibility of designing an oil well filter made from geotextiles. Geotextiles have a porous structure which will allow fluids to pass through while retaining loose sand.

Geotextiles Used For Filtration

The use of geotextiles in engineering applications is relatively new, dating from the 1950 's. The use of geotextiles in Canada has increased in recent years, the primary consumption being in Alberta (J. Mooney, personal communication, January,1989). Geotextiles are defined as permeable textiles used in conjunction with rock, soil, earth or any geotechnical engineering material as an integral part of a man made structure or system (Giroud, 1987). The four main functions of geotextiles are reinforcement, separation, drainage and filtration.

Geotextiles can be classified by their fabric structures. Woven geotextiles are made by interlacing perpendicular yarns. This fabric structure is used more frequently than nonwoven fabrics for reinforcement functions. Nonwoven fabrics are made from staple or filament fibres randomly laid and bonded by mechanical or chemical methods. Nonwovens are most frequently used for filtration and drainage applications.

When choosing geotextiles for filtration three important hydraulic variables must be considered: minimum permeability, maximum opening size and minimum percent open area. Kerr et al (1988) indicate that the sand stress on the geotextile filter used in an oil well may be as high as 1 to 2 MPa. Confining stresses will compress a geotextile and lower its permeability. Scott, Kerr, Richards and Martin-Scott (1988) showed that confining stresses on geotextiles will decrease permeability by 70 to 80%.

In the feasibility study conducted by McClung (1988) the permeability, opening size and strength characteristics for fabrics described in the trade literature were assessed. Nine fabrics were found to be available in the market that could be used for a particular sand gradation found in a heavy oil well. The filtering mechanism is only one of the important criteria to investigate prior to making a final selection of a geotextile for oil filtration. The chemical durability of the geotextile must also be assessed to evaluate whether the fabrics remain chemically and physically stable over the period of time it is to be in service. Durability is dependent not only on the physical and chemical properties of the fibres but also on the physical and mechanical properties of the fabric. The polymers must remain stable over the lifetime of the geotextile filter; for example, the fibres must not swell in the fluids from the oil well because it may affect the permeability and strength of the fabric. Examination of the microscopic (fibre diameter, cross-section) and macroscopic (burst strength) properties of a geotextile will determine the durability of geotextile filter fabric.

Problem Statement

What effects do oil well fluids have on the burst strength and fibre diameter of selected filter fabrics after extended exposure?

Null Hypotheses

1. There will be no significant difference in *burst strength of Q200* specimens after immersion in liquids found in heavy oil wells.
2. There will be no significant difference in *burst strength of Bidimrock TTNT 200/50* specimens immersion in liquids found in heavy oil wells.
3. There will be no significant difference in *burst strength of P0820* specimens after immersion in liquids found in heavy oil wells.
4. There will be no significant difference in *burst strength among the three geotextile* fabrics, before immersion in liquids found in heavy oil wells.
5. There will be no significant difference in *fibre diameter of Q200* specimens after immersion in liquids found in heavy oil wells.
6. There will be no significant difference in *fibre diameter of Bidimrock TTNT 200/50* specimens after immersion in liquids found in heavy oil wells.

7. There will be no significant difference in *fibre diameter of P0820* specimens after immersion in liquids found in heavy oil wells.

8. There will be no significant difference in *fibre diameter among the three geotextile* fabrics, before immersion in liquids found in heavy oil wells.

Assumptions

1. The test fluids used in this study are representative of the liquids found in heavy oil wells in the Norcen Energy Resources Ltd. field located in the Lloydminster area. These wells produce oil at reservoir temperatures.

2. Burst testing simulates the stress that a geotextile will be exposed to in an oil well. The filter is wrapped around a perforated pipe; the oil is pumped through the perforations into the well.

Limitations

1. Results from this study cannot be generalized to all heavy oil wells in Alberta, due to variations in both the geology and recovery temperatures used for oil recovery which affect the properties of the produced fluids.

2. Burst testing may not indicate the actual performance of a geotextile in a heavy oil well since the pressure in a well may not be consistent over a long period of time.

Definitions

ASPHALTENE - Any dark solid constituents of crude oil which are soluble in carbon disulfide but not soluble in paraffin solvents such as pentane or heptane. It has no definite melting point (Aostra, 1983)).

CONVENTIONAL OIL (Light oil) - Any oil that can be brought to the surface by pumping in a well, without using special techniques. It has a low viscosity and a specific gravity of 30-45 °API (Aostra, 1983)).

DENSITY - It is the mass of a given volume. It can be mathematically represented as:

d = mass/volume

The American Petroleum Institute (API) defines oil density in relationship to the specific gravity of water at 60° C. The relationship between specific gravity and API units is represented by the mathematical formula (Burick, 1979)):

$$SG_{60} = \frac{141.5}{^{\circ}API + 131.5}$$

GEOSYNTHETIC - Any synthetic material used with foundations, soils, rock, earth or any other engineering related material, as an integral part of a man-made structure (ASTM, 1987).

GEOTEXTILE - Any permeable textile material used with foundations, soils, rock, earth or any other geotechnical engineering related material, that is an integral part of a engineering project, structure (ASTM, 1987).

HEAVY OIL - Unrefined oil with less than 20°API gravity, high viscosity of greater than 20 centipoise which causes poor reservoir mobility. The chemical content is characterized by greater than 3% weight sulphur, nickel and vanadium content of 500 parts per million, and an asphaltene content up to 50% of its weight (AOSTRA, 1983).

NONWOVEN - Fibres arranged in an oriented or random pattern, into a planar structure. The fibres are bonded together by chemical, thermal, or mechanical methods (ASTM, 1986).

PERMEABILITY - The rate of flow of fluid under a differential pressure through a material (ASTM, 1987).

PERMITTIVITY - The volumetric flow rate of water per unit cross sectional area, per unit head, under laminar flow conditions, in the normal direction through a material (ASTM, 1986).

RESIN - A solid or semisolid organic product, natural or synthetic, without a specific melting point. Most of the compounds contain carbon, sulphur, nitrogen and oxygen atoms (AOSTRA, 1987).

TRANSMISSIVITY - The volumetric flow rate per unit thickness under laminar flow conditions, in the in-plane direction of the fabric (Koerner, 1986).

VISCOSITY - The tendency of a fluid to resist any change in its flow. Flow is the movement of layers of molecules in a regular way with respect to one another. A liquid that flows with ease is decribed as mobile, while one that does not is described as viscous (Boikess & Edelson, 1985).

CHAPTER 2 REVIEW OF LITERATURE

The primary objective of this research is to contribute to the body of knowledge concerning the selection and durability of geotextiles for filtration of oil. The review of literature is composed of four sections. The chemical composition of the liquids found in heavy oil wells, oil and produced water, are discussed in the first section. The process that is used to select geotextiles for filtration applications and the properties of the fibres and fabrics used in this study are described in the second section. The theory of fabric strength is discussed in the third section. In the fourth section, research on durability testing and methods used to measure fibre and fabric properties are discussed.

Characteristics of Heavy Oil Well Fluids

Characteristics of Heavy Oil

Heavy oil, like conventional oil, is composed of saturated and unsaturated hydrocarbons arranged in chain-like or ring-type structures. Saturated hydrocarbons have single bonds between carbon atoms. Unsaturated hydrocarbons have double bonds between carbon atoms which can be broken. The percentage by weight of the common elements found in oil are listed in Table 1.

Table 1

Percentage By Weight of the Elements of Oil

Element	Percent by Weight
Carbon	84.0 - 87.0
Hydrogen	11.0 - 14.0
Sulfur	0.1 - 2.0
Nitrogen	0.1 - 2.0
Oxygen	0.1 - 2.0

(adapted from Burick, 1979)

Deroo, Tissot, McCrossan, and Der (1974) described the chemical nature of the heavy oil hydrocarbons found in the Mannville Group, a geological formation in the Lloydminster area. Compared to conventional oil, heavy oil hydrocarbons show a lower alkane content, and a higher proportion of phytane and pristane isoprenoid compounds. The isoprenoids are found where the water has a total salinity of greater than 80 parts per thousand.

Hodgson and Baker (1959) described the basic chemical characteristics of heavy oil found in the Lloydminster area. Overall, the percentage of all metals including nickel and vanadium is higher in heavy oils than conventional oils. Breger (1979) found that the mean concentration of vanadium in conventional oil is 0.1 ppm, whereas heavy crude oil may contain up to 3000 ppm of vanadium. The concentration and location of vanadium affects the physical properties of oil, such as flow and viscosity. The nickel content correlates with the asphaltenes, resins, vanadium, and sulphur content in heavy oil. The sulphur content is found in higher quantities in heavy oil than conventional oil (Yen, 1975).

Characteristics of Produced Water

Water, often referred to as interstitial water, is found in oil reservoirs. The water has a high content of dissolved salts, usually higher than the salt content of seawater. The most common cations present are sodium, potassium, calcium, and magnesium. The most common anion is chlorine. Sulfur dioxide and hydrochloric acid are also present. It is virtually impossible to measure the viscosity of reservoir water below the ground, therefore it is assumed to be equal to the viscosity of distilled water (Burcik, 1979).

Fibres and Fabrics

Fibre Morphology

Elais (1977) and Billmeyer (1984) discussed the arrangement of molecules within the polymer structure. Molecules are bonded together by ionic and covalent bonds. Covalent bonds may be polar or nonpolar. Ionic bonding is the result of electron transfer from one atom to another. For example, in sodium chloride (NaCl), sodium (Na^+) is positively charged and is attracted to chlorine (Cl^-) which is negatively charged. A covalent bond results from the sharing of a pair of electron by two atoms (Fessenden & Fessenden, 1986). If the atoms sharing the electron pair have equal electronegativity, the bond is nonpolar. If they differ in electronegativity, the sharing is unequal and the bond is polarized. The higher the degree of polarity, the greater the ionic character of the bond. An important type of intermolecular force is the hydrogen bond. In a hydrogen bond, the hydrogen atom is covalently bonded to an electronegative atom and is attracted to the unshared pair of electrons of an adjacent electronegative atom. Water is a polar solvent with hydrogen bonding. Fibres with polar groups will attract water, and thus, exhibit good moisture absorption (Van Krevelen, 1976). A type of attractive force important in fibres is the dipole-dipole interaction. Dipole-dipole interactions, collectively called van der Waals forces, occur when an electron from one atom is attracted momentarily to the nucleus of a second atom. In fibres, the polymers are closely packed so that atoms in one polymer chain are attracted by Van der Waals forces to the atoms of an adjacent chain. The polymer chains must be very close for this attraction to occur. This type of molecular bonding forms the basis for the structure of a specific fibre. In polyester and polypropylene fibres, bonding consists primarily of van der Waals forces. The lack of polar groups contributes to their hydrophobic properties.

The fringed micelle theory or fringed crystallite model depicts the structure of molecules within a fibre (Billmeyer, 1984). Long chains of molecules group together to form crystalline micelles. During crystallization, the molecules fold back on themselves, thus micelles consist of folded chains. Between the micelles, the molecules are not aligned; these areas are known as the amorphous regions. The long chain molecules may pass from one crystalline micelle region to an amphorous region and into a second crystalline region. Taut tie molecules link the crystalline regions and determine the strength of the fibre (Elais, 1977 ; Van Krevlen, 1977). The morphology of a polymer is determined by the relative amount of irregularly arranged molecules (amorphous regions), the folded chain molecules (crystalline regions) and the number of extended chains of micelles (tie molecules) (Van Krevlen, 1977). Figure 3 illustrates the morphology that is typically found in polymer structures.

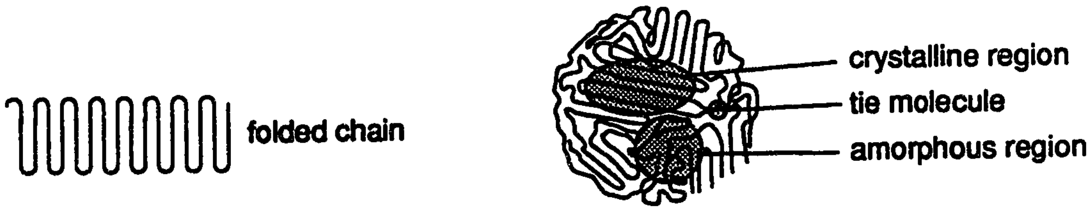


Figure 3 Arrangement of Molecules in a Fibre
(adapted from Wunderlich, 1973)

The degree of orientation in the fibre is determined in the drawing stage of manufacturing (Billmeyer, 1984). After extrusion through a spinneret, fibres are drawn by placing the fibres under stress which increases the alignment of the molecules. The folded molecules move such that they are oriented with the fibre axis. The amorphous regions remain unoriented with space or free volume between the molecules. Figure 4 illustrates the movement of chain segments during the drawing stage.

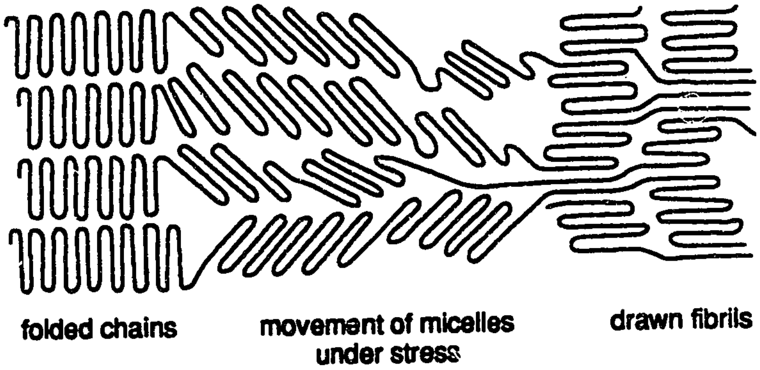


Figure 4 Movement of Chain Segments in a Molecule During Drawing (adapted from Peterlin, 1967)

The Effect of Solvents on Fibre Swelling

The free volume in the amorphous regions of fibres is the site where solvents may enter the fibre, resulting in fibre swelling and dissolution. The swelling of fibres when immersed in a liquid is estimated by the solubility parameters (α) of the liquid and the polymer. If the fibre and solvent have similar solubility parameters they will probably interact with one another (Gardon, 1971).

Gardon (1971) and Peiffer (1980) discussed the influence of molecular bonding on the solubility parameter of a fibre. In the presence of polar bonding, fibres will tend to swell in solvents with similar solubility parameters. Nonpolar bonded fibres, those with van der Waals forces, will not swell in polar solvents. In effect, for fibres to dissolve in solution, the difference in the solvent and fibre solubility parameter must be negative and the bonding forces within the fibre and solvent must be similar. Van Krevlen (1976) stated that the solubility parameter of a liquid may vary from ± 0.8 to ± 3.4 cal $^{0.5}$cm$^{-1.5}$ of the polymers solubility parameter. Water ($\alpha = 23.2$) is a polar solvent and will not interact with polyester ($\alpha = 10.7$), a nonpolar fibre whereas, aromatic hydrocarbons like benzene ($\alpha = 9.15$) will probably swell polyester because their solubility parameters and intermolecular bonding forces are similar (DeKock and Gray, 1980). The solubility parameter (d) of a fibre is determined by the free energy of mixing and can be mathematically calculated by the following equation.

$$d = (CED)^{1/2} = (\Delta E_v/V)^{1/2}$$

CED = cohesive energy density, a measure of the strength of the molecular forces holding the molecules together in liquid state
E_v = molar change in internal energy upon vaporization
V = molar volume of the liquid

(Gardon, 1971)

Diffusion of solvents into the fibre structure occurs via the amorphous regions. The diffusion coefficient in a fibre is higher perpendicular to the fibre axis than longitudinally due to orientation of the crystalline micelles. Meredith (1946) stated that since molecules are preferentially oriented to the fibre axis after drawing and crystallites do not swell, swelling in the amorphous regions occurs laterally. Rusznak (1983) explained the mechanism of solvent penetration as solvent molecules penetrating the amorphous regions. The less space between crystalline regions the lower the probability of swelling. Solvents are absorbed into the amorphous regions causing the crystalline micelles to be pushed apart, increasing the distance between crystalline regions. Unless a liquid is a very powerful swelling agent for a particular polymer it will not enter the crystalline regions.

Selection of Geotextiles for Filtration

It is important to consider the end use of a geosynthetic textile when selecting a material for an engineering design. A functional design capitalizes on the characteristics of the materials which become an integral part of the design. Williams and Luna (1987) suggested that selection of a geotextile used for filtration should be based on the filtration characteristics, flow capacity, strength behavior, compatability with fluids and soil, durability and cost; specifically, the filter must be permeable and durable over its lifespan.

Nonwoven geotextile fabrics have a web structure that allows fluids to flow through the open spaces, making them suitable for a filter design. The geotextile filter will be exposed to confining stress from the sand. The sand collapses against the well completion. Using data from Schober and Teindle (1979) Kerr et al (1988) plotted the compression (%) versus the confining stress. They showed that the confining stress approached 1 MPa at a compression of the geotextile of about 80%. Kerr et al (1988) stated the criteria for a geotextile filtration fabric: it must be able to withstand 1 to 2 MPa of sand pressure and be chemically resistant to the fluids in the well. The confining stress of the sand against the well completion was estimated to be 1 to 2 MPa. Based on these criteria, McClung (1988) evaluated the properties of geotextiles available in the market place and selected nine needle punched nonwoven fabrics that theoretically may be successful for filtration of heavy oil. Wong (1990, personnal communication) tested the permeability of these nine fabrics and selected three of them for further testing in heavy oil. These fabrics are the focus of this durability research. Two of the three fabrics are composed of polyester fibres and the other fabric is composed of polypropylene fibres.

Properties of Polyester

The most common polyester is polyethylene terephthalate which is usually formed by combining terephthalic acid with ethylene glycol in a direct esterification and polycondensation reaction. During direct esterification the alcohol, ethylene glycol, reacts with the acid , terephthalic acid, at the carbonyl oxygen (McIntryre, 1985 ; Brown & McClarin, 1981). The carboxylic acid fundtional groups provide protons to catalyze the reaction or another acid catalyst is added.During the second step, polycondensation occurs. Another catalyst, such as antimony trioxide, is added to the mixture of linear oligomers, the free glycol is distilled out of the vat and the temperature is raised to 280 to 290 °C. The pressure is reduced and polymerization occurs until the desired molecular weight has been attained (McIntryre, 1985). The reason the polymer formation can occur is that the reactants are bifunctional, thus each reactant can undergo reaction with two other molecules to form a long chain polymer (Fessenden & Fessenden, 1986). The esterification and polycondensation reaction are shown in Figure 5.

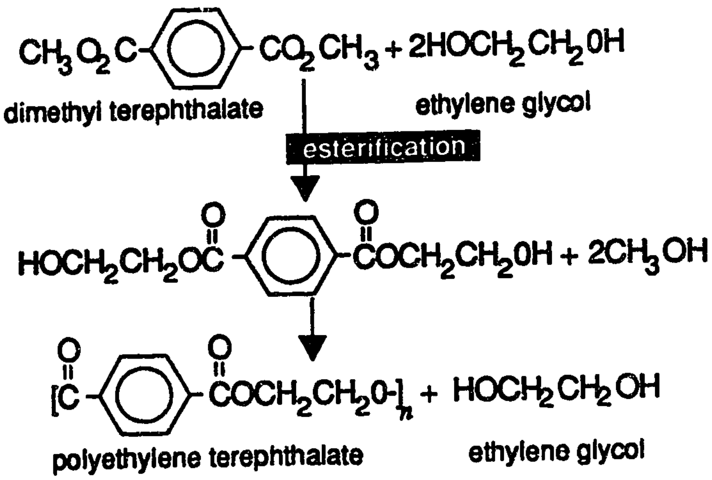


Figure 5 Polymerization of Polyethylene Terephthalate (adapted from Stevens, 1975)

The filaments are formed by melting polymer chips and extruding the liquid through a spinneret. The strength of polyester filaments is determined during the drawing stage. If the draw ratio is high the molecules become oriented to the fibre axis and to one another to form crystalline regions (Moncrieff, 1975). The typical crystallinity of polyester is 65 to 85% (Gohl & Vilensky, 1985).

The molecular weight of polyester ranges from 15,000 to 30,000 (Davis, 1988). McIntryre (1985) suggested that molecular weight is an important feature of polyester because at a given molecular weight the melt-spinning and orientation processes will be unique to that molecular weight. These processes affect physical properties such as tensile strength. If high orientation occurs during the drawing of the filament, the tenacity and tensile strength of the filament will be high while the extensibility of the filament will be low. High molecular weight results in high work to break. Pajgrt and Reichstadter (1979) suggested that the molecular weight of a fibre reflects the degree of crystallinity within the fibre. Fibres with high molecular weights have long polymer chains. In polyester, the long linear chains with no bulky side groups are tightly packed together and held by van der Waals forces.

In an acid solution, the carbonyl oxygen of an ester may be protonated. The partially positive carbon may be attacked by weak nucleophiles, such as water, to produce one hydroxyl and one carbonyl end group (Fessenden & Fessenden, 1986). Polyester may be hydrolyzed in some acidic conditions. For example, chlorosulphonic acid immediately dissolves polyester. After one year of immersion at room temperature, in acids such as hydrochloric acid (20%), polyester will be degraded (Davis, 1988). The hydrolysis reaction is shown in Figure 6.

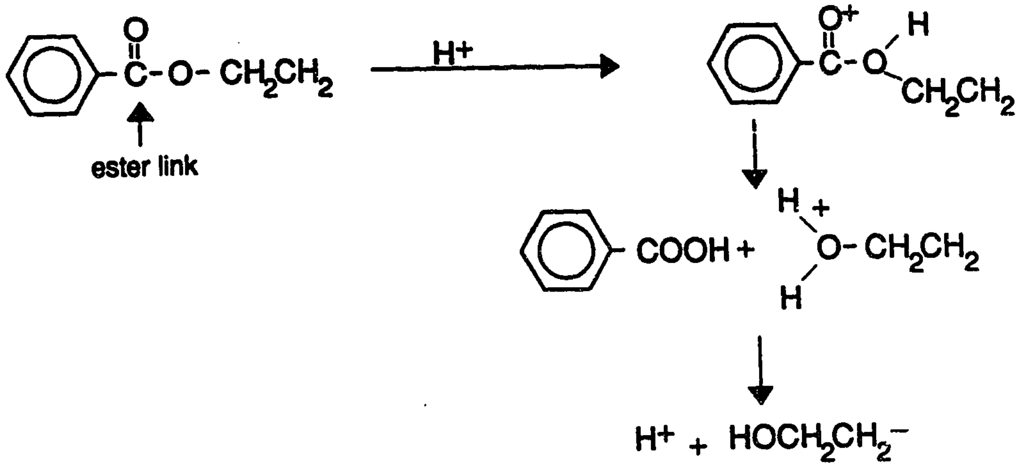


Figure 6 Hydrolysis of Polyester in Acidic Conditions (McIntryre, 1985)

Polyester is susceptible to damage in alkaline conditions. As in the case with acids, alkaline degradation increases with increased temperature, increased concentrations and long exposure times (Davis, 1988). Polyester is severely degraded by ammonia and caustic solutions at high concentrations. Alkaline hydrolysis is damaging because it is an irreversible reaction, whereas, acid hydrolysis may be reversed. The nucleophilic attack occurs on the ester linkage, resulting in the reduction of an ester to produce one hydroxyl and one carboxylate endgroup (Fessenden & Fessenden, 1986). Hydrolysis in aqueous acids is slower than in an aqueous alkali. Polyester immersed in 30% hydrochloric acid will lose half of its strength in three days at 70 °C, whereas in 30% sodium hydroxide, polyester will be destroyed in less than three days (McIntryre, 1985). The alkaline hydrolysis reaction is shown in Figure 7.

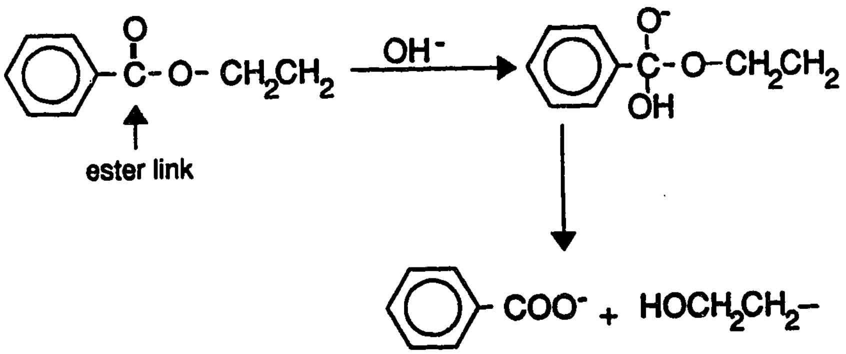


Figure 7 Hydrolysis of Polyester in Alkaline Conditions (McIntryre, 1985)

It is important to consider the polar and nonpolar intermolecular forces when studying chemical compatibility of a solvent and polymer. Polyester acts as two chemically distinct alternating aromatic and aliphatic residues when it is immersed in a solvent. Knox, Weigmann and Scott (1975) studied the solubility parameters (α) of polyester and concluded that it had two solubility parameters: $\alpha = 9.8$ cal $^{0.5}$cm$^{-1.5}$ and $\alpha = 12.1$ $^{0.5}$cm$^{-1.5}$. A solvent with a solubility parameter close to the solubility parameter of 9.8 of polyester, interacts with the aromatic residue, whereas, solvents with a solubility parameter of 12.1, interact with the aliphatic ester (Figure 8).

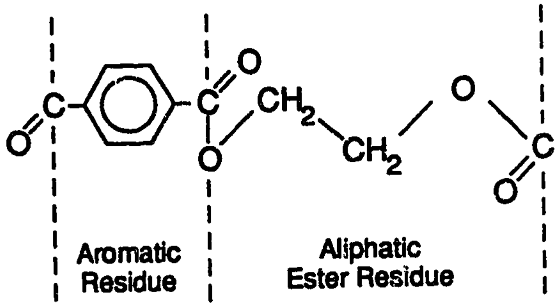


Figure 8 Aromatic and Aliphatic Components of Polyethylene Terephthalate (adapted from Knox, Weigmann & Scott, 1975)

Some solvents do not interact preferentially with either group but are attracted to both aromatic and aliphatic residues. For example, n-hexanol ($\alpha = 10.7$) interacts with polyester at both residues. This behavior agrees with the solubility parameter of polyester ($\alpha = 10.7$) which is the average value between the two solubility parameters (Knox, Weigmann & Scott, 1975; Gardon, 1971). In Table 2 numerous solvents and their solubility parameters (α) are listed with the swelling (%) of polyethylene terephthalate fibres after they were immersed for 90 days at room temperature.

Given that polyester will hydrolyze at the ester linkage in acidic conditions, solvents with a solubility parameter ($\alpha = 9.8$) may hydrolyze polyester at the aromatic linkage causing it to swell. Solvents with solubility parameters of 9.8 to 10.8 cal$^{0.5}$cm$^{-1.5}$ caused 2.4 to 13% swelling in polyester, which may indicate interaction with the aromatic residue (Knox et al, 1975). Solvents with a solubility parameter of 12.0 cal $^{0.5}$cm$^{-1.5}$ caused polyester to swell from 2.4 to 8.0% which may indicate interaction with the aliphatic ester (Knox et al, 1975). The solvents act as nucleophiles causing hydrolysis at the ester linkage. In comparison, sulphur compounds typically found in oil, have solubility parameters ranging from 10.0 to 14.6. Aliphatic hydrocarbons and aromatic hydrocarbons, also found in oil, have solubility parameters ranging from 6.7 to 9.2 cal $^{0.5}$cm$^{-1.5}$. These solvents all contain nonpolar bonds, like polyester, which may increase the chance of polyester swelling in oil fluids (Gardon, 1971).

Table 2

The Percentage of Swelling of Polyester Fibres after Immersion in Various Solvents for 90 Days at Room Temperature

Solvent	Swelling (%)	Solubility Parameter (cal $^{0.5}$cm$^{-1.5}$)
Benzenaldehyde	11.07	10.8
Analine	13.20	10.8
Carbon disulfide	2.61	10.0
Chlorobenzene	5.70	10.0
n-butanol	0.72	11.4
Dimethylformamide	8.32	12.1
Ethanol	2.36	12.2
Toulene	0.20	8.9
Cyclohexane	0.00	8.2
Water	0.00	23.2

(adapted from Knox, Weigmann & Scott, 1975; Gardon, 1971)

Davis (1988) immersed polyester for a year in various acidic and alkaline solvents. Table 3 lists solvents that affect the strength of polyester after immersion for one year at room temperature. Generally, polyester is resistant to most acids; for example, the strength of polyester is not reduced when it is immersed in weak sulfuric acid, formic acid and nitric acid for one year. Alkaline solvents tend to cause strength loss in polyester fibres; ammonium hydroxide and sodium hydroxide severely degrade polyester fibres. Inorganic salts and organic salts such as sodium bisulfite and ammonium sulfide have very little effect on the strength of polyester. Benzyl alcohol and tetrachloroethane caused polyester to lose strength after one year immersion (Davis, 1988).

Halse, Koerner and Lord (1987) also studied the affects of high alkalinity on the tensile strength of geotextiles and found that polyester fabric lost 30% of its strength after 120 days at pH 12. After periodic testing it was concluded that strength loss for polyester occurred early in the test interval, reached a maximum strength loss and remained at that value for an extended time.

Table 3

Resistance of Polyester after Immersion in Various Solvents for One Year at Room Temperature

SOLVENT	RESISTANCE OF POLYESTER
Chlorosulfonic acid	degraded
Hydrochloric acid (20%)	degraded
Inorganic bases	hydrolysis
Organic bases	aminolysis
Benzyl alcohol	dissolved
Halogenated phenol	dissolved
Sulfur compounds	dissolved
Ammonium hydroxide (2%)	severely degraded
Sodium hydroxide (2%)	severely degraded
Sodium bisulfite	severely degraded
Ammonium sulfite	severely degraded
Tetrachloroethane	degraded

(adapted from Davis, 1988)

Properties of Polypropylene

Polypropylene is a long linear chain polymer, with pendant methyl groups regularly positioned with respect to the carbon backbone. Its chemical structure may be isotactic, with all methyl groups spacially arranged in the same plane, syndiotactic, with methyl groups alternating on two planes, or atactic, with irregularly distributed methyl groups on two planes. Typically, polypropylene fibres are formed with an isotactic molecular structure as shown in Figure 9.

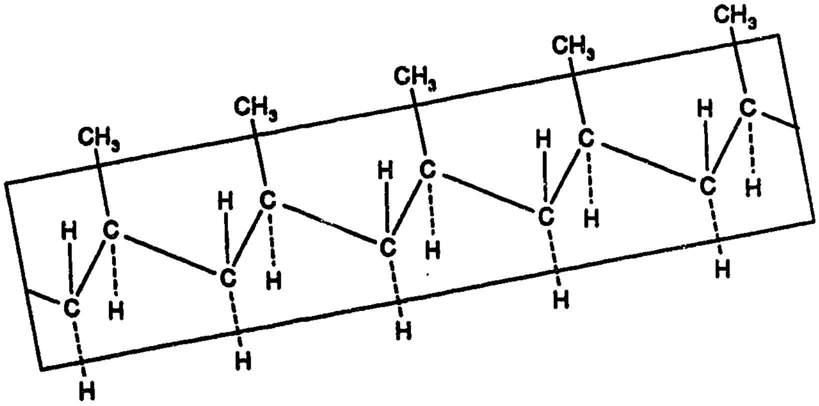


Figure 9. An Isotactic Polypropylene Polymer; (adapted from Vittoria, 1989)

The isotactic polymer crystallizes in a helical conformation in which alternate chain bonds take trans and gauche positions, generating either a left or right hand helix. The helix has three methyl groups per turn (Billmeyer, 1984). Isotactic polypropylene is produced by the addition polymerization of propylene. A Ziegler-Natta catalyst, titanium trichloride and co-catalyst alumimium triethyl are used to control the formation of the polymer such that a stereoregular polymer with methyl groups in one plane is formed (Fessenden & Fessenden, 1986).

Polypropylene is a semi-crystalline polymer with a molecular weight ranging from 100,000 to 300,000. The polymer structure may have a degree of crystallinity ranging from 50 to 65% (Wishman & Hagler, 1985). Spherulites form around a nucleus and alignment of the molecular chain segments causes crystallization to be initiated. The lamallae expand in the shish-kabob structure before drawing the fibre (Wishman & Hagler, 1985). Depending on the temperature during drawing the proportion of amorphous, crystalline and smetic regions will vary. The smetic region is the semidisordered state which is formed when isotactic polypropylene is rapidly cooled during drawing (Vittoria, 1989). At a moderate drawing temperature, polypropylene will contain amorphous noncrystalline regions, crystalline regions and intermediate smetic regions.

Unlike polyester, polypropylene is highly resistant to alkaline conditions and acidic environments. Results from a two part study conducted by Halse et al (1987) indicated that nonwoven polypropylene fabric retained 92% of its strength after being exposed to sodium hydroxide for a year (pH 12) and increased in strength by 10% when it was exposed to calcium hydroxide (pH12) for one year. Polypropylene is resistant to various acids, alkalis, cold organic solvents and miscellaneous solvents. Hot decalin™ (decahydronaphthalene) which dissolves most ketones and esters and used as a lubricant in motor oil, will dissolve polypropylene (Merck Index, 1983). Perchloroethylene, tetrachloroethane and white spirits will also degrade polypropylene (Moncrieff, 1985; Aiyangar & Hardin, 1981).

Vittoria and Riva (1986) studied the relationship between the crystallization of polypropylene and its solubility parameter. Polypropylene was immersed in various solvents for 24 hours and for 10 days at room temperature to determine how the rate of swelling changes over time. After 10 days immersion in the solvents, penetration of the solvent into the polypropylene had equilibrated and in effect, the swelling was slightly lower than it had been at 24 hours. It was concluded that the solubility parameters of polypropylene are $\alpha = 8.1$ and 9.2-9.4. The amorphous and smetic regions in the polymer structure react differently to solvents. Given that solvents with bonding characteristics and solubility parameters similar to a polymer will swell the fibre, compounds found in oil, such as, aromatic and aliphatic hydrocarbons ($\alpha = 6.7$ to 9.2) may increase the probability of polypropylene swelling in oil. Table 4 lists the percent swelling of polypropylene fibres in various solvents with given solubility parameters.

Table 4

The Percentage of Swelling of Polypropylene Fibres after Immersion in Various Solvents for 24 Hours

Solvent	Swelling (%)	Solubility Parameter (cal$^{0.5}$cm$^{-1.5}$)
n-hexane	6.0	8.2
Cyclohexane	15.0	8.2
Toulene	8.1	8.9
Carbontetrachloride	15.0	8.6
Chlorobenzene	8.3	10.0
Dichloromethane	4.1	9.7

(adapted from Vittoria and Riva, 1986 ; Gardon, 1971)

Fabric Property Measurements

Williams and Luna (1987) suggest three types of laboratory testing for geotextiles: control tests, index tests, and design tests. Control tests for geotextiles include tests such as thickness and mass per unit area. These tests are usually carried out by the manufacturer to ensure quality control. Index tests are standard tests used to evaluate properties such as the strength of the fabric and hydraulic properties. Trade literature usually reports these measurements. Design tests simulate conditions which the geotextile will have to withstand in the field. The focus of the present study is to determine changes in fabric properties using index tests.

Theory of Fabric Strength

The strength of a nonwoven fabric is determined by the fibre properties, the geometrical arrangement of fibres in the web structure and the bonding between fibres. Fibre properties are determined by intermolecular bonding, orientation of chain molecules with respect to the fibre axis, cross-sectional fibre shape, fibre length, crimp and surface contour (Gupta & Paradkar, 1985; Kaswell, 1953).

Morton and Hearle (1975) discussed the relationship between the strength of a fibre and the molecular weight of the polymer. For linear polymers like polyester and polypropylene, the higher the molecular weight, the more rigid the fibre will become. Factors that affect rigidity will also affect the strength of the fibre, for example, fibre shape, density and thickness of the fibre.

The theory explaining the deformation of nonwoven fabrics under stress is comparable to spun yarn theory. In a spun yarn, when it is placed under tension, the fibres grip one another due to transverse forces generated in the yarn. The more transverse the lay of the fibres that is, the steeper the angle the fibres make relative to the main axis of the yarn, the weaker the strength of the yarn. Maximum yarn strength is reached when the amount of twist in a yarn is such that the loss of strength due to obliqueness of the fibres in the yarn is offset by the gain in transverse forces which holds the fibres together. In a nonwoven fabric, the strength decreases as the fibre entanglement is more parallel to the machine direction of the fabric because the strength will be weaker in the cross direction of the fabric.

In the early stages of deformation the fibres slip past one another. The friction bonding among adjacent fibres determines the extent that the fibre is able to move. The fibres move from side to side and top to bottom through the web structure. As tension increases the stress is passed along the fibres; at some point the load is too great for the fibres to absorb the energy and failure occurs.

Hearle and Stevenson (1964) concluded that the fibre curl distribution or crimp influences the bond friction among fibres and the initial modulus of the stress-strain curve. The initial modulus will be high if the fibres contain high crimp. Gupta and Parakar (1985) studied the rupture properties of nonwoven fabrics and calculated the probability of a fibre being gripped at both ends by the entanglement with other fibres in the fabric. If this occurs, the probability of breakage will increase.

Pierce (1926) developed the weakest link theory; the strength of a fabric is equal to the strength of the shortest yarn in the fabric. The 'chain of bundles' model assumes when a yarn breaks, the load that broke the yarn is equally shared by all the remaining yarn segments. The strength of a bundle is determined when the weakest bundle fails under an applied load. Local load sharing occurs when the yarn breaks. After breaking, the share of load borne by the yarn which broke is transferred to the yarns closest to the broken yarn. Booth (1969) cautioned that the extensibility of the yarns and the fabric structure determine the strength of the fabric. Stronger yarns may be less extensible and therefore, may break before weaker yarns that are more extensible.

Laboratory Testing

The physical tests used to determine geotextile durability may involve macroscopic or microscopic test procedures. Microscopic test procedures measure small changes in fibres: birefringence, diameter, surface appearance and morphology. Macroscopic tests measure physical changes in tensile or burst strength, extensibility and abrasion resistance. The end use of the geotextile will determine the test chosen.

Durability Testing

Leflaive (1989) compared long term durability tests with laboratory aging tests and concluded that it is difficult to simulate field conditions. For example, the conditions found in an oil well may differ from the simulated conditions in the laboratory. Oil and produced water are not miscible solvents, so that the test procedure must incorporate a method to determine the effect each liquid will have on the fabrics and the combined effect of both liquids on the fabric. During aging tests, changes may occur to the physical properties of fibres such as thermal relaxation of stressed fibers, swelling or plastization and surface etching or coating. These changes affect the strength of the geotextile. In order to determine the chemical stability of the fabric, each independent variable must be manipulated in a controlled environment.

The temperature and amount of time taken to perform aging tests may influence the estimated life expectancy of a fabric. At various elevated temperatures, properties may be tested at selectedintervals. After testing, the life expectancy of the fabric may be determined by extrapolation of plotted results on a graph. Extrapolation, however, can lead to erroneous conclusions. Hawkins (1984) discussed the relationship between time and temperature when predicting life expectancy of textiles. The graph in Figure 10 shows the extrapolation of accelerated aging test results. There are three situations that may occur if the results are incorrectly extrapolated. If the test results are extrapolated following line B, when the rate of degradation increased near the end of its service life, the service life of the fabric would be shorter than the time that is predicted from the graph. If the rate of degradation of the fabric slows down or reaches a minimum when line C is used for extrapolation, the life of the fabric would be longer than the time predicted from the graph. The linear relationship, line A, is the only result that can be accurately extrapolated to estimate the service life of a geotextile.

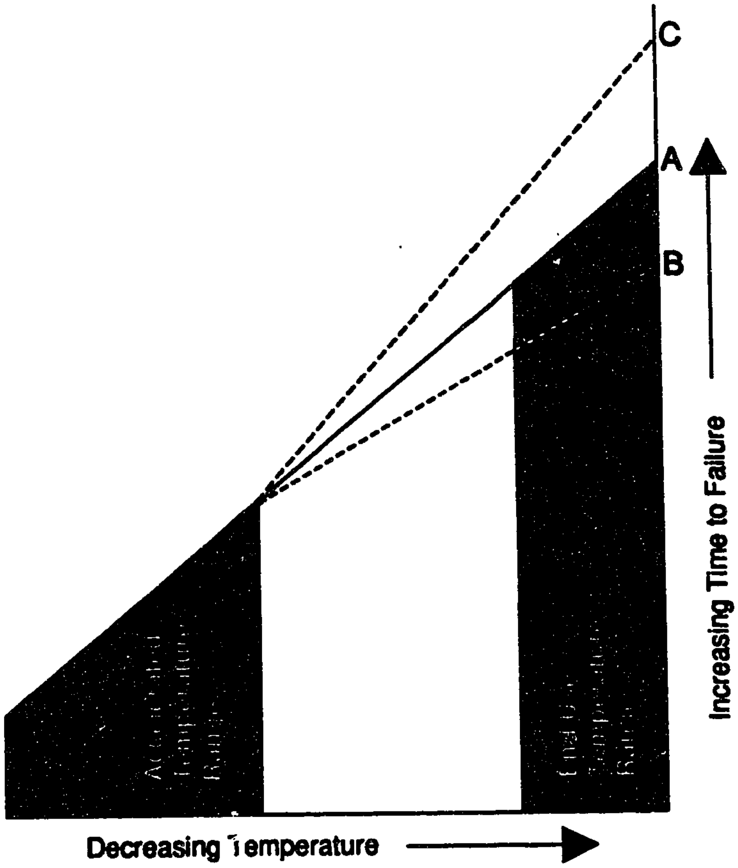


Figure 10 Linear Extrapolation of Aging Tests; (adapted from Hawkins, 1985)

Thomas and Verschoor (1988) and Richardson and Koerner (1988) used accelerated aging tests to determine the service life of a geomembrane. The geomembrane was placed in a column with soil on each side, then a solution was added. By increasing the temperature, the rate of reaction of the geomembrane at various temperatures is measured with microscopic tests. The results are applied to the Arrhenius equation. It is assumed that the rate constant derived from the Arrhenius equation using accelerated aging data is comparable to the rate of reaction obtained in a field test. The Arrhenius equation is shown below.

$$K = A e^{-E/RT}$$

where:

K = rate constant
A = constant
E = reaction activation energy (cal/g-mole)
R = gas constant (1.986 cal/g-mole - °K)
T = temperature (°K = 273° + °C)

(Koerner & Richardson, 1987)

Other assumptions made by Koerner and Richardson (1987) were that the solvents were representative of the sample, the experimental set was realistic, the elevated temperature did not alter the chemical structure of the geosynthetic and the Arrhenius extrapolation of time equivalency was valid (Koerner & Richardson, 1987).

The Matrecon test method was a valuable resource for the development of the Environmental Protection Agency (EPA) method 9090. Landeeth (1983) used the Matrecon Test Method to determine the compatibility of membrane liners with waste solutions. The selected geosynthetics were immersed in a solution at 27°C and at an elevated temperature and were tested periodically from 120 days to one year.

The EPA method 9090 was developed in the early 1980's to determine the compatability of geomembranes with waste containment liquids. It specifies that testing should be performed at ambient (20 °C) and/or elevated (50 °C) temperatures. Recently,it has been revised to test geotextiles and other geosynthetic products. Before and after immersion in solution, physical and mechanical tests are performed to measure changes in the performance of the geotextile. For geotextiles, test measurements recommended are mass per unit area, grab strength, puncture, trapezoidal tear, hydrostatic burst strength and water permeability. White and Verschoor (1989) reviewed EPA method 9090 and made the following suggestions for geotextile applications: random sampling of specimens is essential to ensure a representative sample; due to the variability in weight and thickness of geotextiles many test replications should be performed at each time interval; and specimens should be tested either all-wet or all-dry after immersion in fluids.

Koerner and Richardson (1987) compared accelerated aging tests with the EPA method 9090 for determining chemical compatibility of geosynthetics with various chemicals. EPA method 9090 follows parallel steps to accelerated aging tests. EPA method 9090 uses a chemical solution in which the geosynthetic is immersed at 27 °C or an elevated temperature. The geosynthetics are tested at selected intervals from 120 days to 1 year. Physical tests are used to determine percent change in performance and evaluate the suitability of the geomembrane for its end use. It was concluded that the EPA method 9090 is an acceptable method for determining chemical compatability of geosynthetics but eliminates costly, time consuming procedures used to determine the rate of reaction in the Arrhenius model.

Landeeth (1983) and Cloa, Sherman and Haxo (1987) studied the compatability of geomembranes in waste containment fluids using EPA 9090. In both these studies specimens were hung in a tank with all surfaces of the geomembrane exposed to the solution. In cases where the components of the solution separated, an increased number of specimens was used in order that specimens could be exposed to each chemical solution. After immersion the specimens were wiped and cleaned, then placed in bags so they would not dry.

Montalvo (1989) evaluated the strength of polyester and polyproplyene after exposure to jet and diesel fuel for 7, 14, 28, and 56 days. All specimens were tested at room temperature (23°C ± 2°C). Both geotextiles remained stable over a 56 day period.

Strength Testing

Sissons (1977) stated that strength is an important property to consider in engineering applications. There are three basic ways of testing strength: tensile, burst and tear. The tensile method stretches the fabric within its own plane. Similarly, the burst method strains the fabric normal to its own plane but causes deformation in the third dimension. The tear method applies a load to a point with shearing action.

The theory explaining the tensile strength of a fibre is valuable for understanding the mechanics of the burst test. When a fibre is placed under stress, the strain or extension recorded is a measure of the change in the dimensions of the fibre. The initial modulus of the fibre indicates the stress that can be placed on a fibre without irreversible deformation of the fibre. There will be extension but no breakage of the fibre bonds at this stage. The point at which the fibre will no longer return to its original form is known as the yield point. Beyond this point, the bonds between the fibres will break and creep and irreversible damage will occur. The point at which the fibre breaks will determine the strength of the fibre.

Richards and Scott (1986) compared the ravel strip, grab tensile and wide width tensile tests for fabrics. The ravel strip method is an accurate method for woven fabrics but it cannot be used on nonwoven fabrics. The grab test is the simplest test used to determine the tensile strength of fabrics. Generally, the grab test records higher tensile strength than the wide width test. The wide width tensile test for geotextiles has been successfully used on woven fabrics but has not shown the same reliability when it is used on nonwoven structures. The burst test has traditionally been used on knitted and nonwoven fabrics to measure the tensile strength. The fabric is deformed biaxially into a third dimension until the fabric breaks. In a fabric, the yarns with the least extension control the burst strength because they are the first to reach their breaking extension and fail. The measurement recorded determines the deformation a fabric can withstand at rupture.

Athey (1980) confirmed that fabrics of equal tensile strength may have different bursting strengths. The yarns in a fabric may be able to move into a third plane allowing high extension and a higher burst strength may result. The relationship between burst test results and actual fabric performance have not been correlated.

Microscopic Analysis

Changes in Fibre Diameter

Fibre diameter is a measurement used to characterize fibres. Generally, most manufactured fibres have relatively consistent fibre diameter measurements compared to natural fibres. Fibre diameter measurements are made by mounting fibres in a medium that will not alter the morphology of the fibres then examining them with a light microscope which and a calibrated eyepiece micrometer. The refractive index of the mounting medium should be distinct from the refractive index of the fibre.

Changes in fibre diameter, after a fibre has been exposed to various solutions, may indicate the fibre structure has been altered. Oleophilic, or oil loving fibres like polyester and polypropylene would be expected to swell in oil. By estimating the solubility parameters and measuring fibre diameter, quantitative data can be obtained to determine the effect of oil and produced water on fibre morphology.

Scanning Electron Microscopy

The purpose of using microscopic examination is to produce high magnification to observe minute fibre details particularly surface morphology. The scanning electron microscope (SEM) is a well suited instrument for textile research. Since fibres are small and may be easily imaged on the SEM, fibre features may be observed with relative ease (Billica and Van Veld, 1975). The scanning electron microscope (SEM) has an electron beam that scans the specimen. The low electrical conductivity of fibres makes metal coating a requirement for imaging because synthetic fibres build up a charge during the scanning process. The electrical charge buildup in the elements is conducted through the coating of gold or silver. The image is an enlargement of the specimen being observed. The advantages of using SEM are: fibre examination with little damage to the fibres; the preparation of specimens is relatively simple; the high resolution of the fibre image allows for detailed investigation of the surface of the fibre; and good depth of field.

Hearle, Lomas, Cook and Duerden (1989) compiled results of numerous studies investigating the failure of fibres. Using the scanning electron microscope, distinct surface characteristics of a fibre could be identified from different kinds of stresses placed on a fibrous structure. Visual comparison of the undamaged fibre appearance and the damaged fibre appearance shows the degradation that has occurred.

CHAPTER 3 MATERIALS AND METHODS

Experimental Design

The dependent variables in this study are burst strength and fibre diameter. The independent variables are the three types of fabric and the three immersion fluids. The fabrics are: Q200™ manufactured by Wellman QuLine Inc., Charlotte, N.C., Bidimrock TTNT 200/50™ manufactured by Rhone Poulenc, and P0820™ manufactured by Exxon. The immersion fluids are heavy oil, produced water and distilled water. Fabric specimens were immersed in the three fluids for 0, 15, 30, 60 and 120 days at room temperature (21 to 24 °C). Burst strength and fibre diameter were measured to determine if there were physical or mechanical changes to the characteristics of the fabrics. There was a total of 15 different test conditions for each fabric type.

Geotextile Fabrics

In a preliminary study McClung (1988) identified nine potential geotextile fabric types for heavy oil filters by assessing hydraulic, physical and mechanical properties reported in the trade literature. Wong (1990, personnal communication) tested seven of the nine fabrics for hydraulic properties, using the gradient ratio test. From the results of this test, which measures the clogging potential of the filter and the rate of flow of water through the test soil filter and geotextile filter, three fabrics were selected for further hydraulic testing and durability testing. The focus of this research was to test the durability and chemical compatibility of selected geotextiles after immersion in heavy oil and produced water.

Two of the selected fabrics Q200™ and P0820™ have a nonwoven needle-punched construction. A needle-punched fabric is manufactured by extruding fibres from a spinnerette. The fibres are blown with air currents into a randomly oriented web, then placed on a conveyor that moves through a needle-punching machine. The barbs of the needles in the machine penetrate the fabric to entangle the fibres, creating a mechanically bonded nonwoven structure (Joseph, 1986). The third fabric, 200/50 TTNT™, is a malimo construction with a scrim attached to one side of a needle-punched web. Ponitz (1977) and Kecma (1971) describes a malimo construction. The first step in construction of this fabric is to manufacture the web structure. It is mechanically needle-punched using the same method described above. Two sets of yarns are laid over the web in the warp and weft direction. A third set of yarns is used to sew-knit or stitch bond the scrim yarns to the web structure.

Specimen Preparation

Specimens measuring 8cm^2 were cut from the test fabrics and randomly selected for immersion in the test fluids, according to CAN/CGSB-148.1 NO.1-M85. Ten specimens from each fabric were immersed in each of the three fluids for each of the five intervals (0, 15, 30, 60, 120 days). In total, 50 specimens were required for each fabric type in each immersion fluid. Mass, thickness, fibre diameter and bursting strength were measured for the day zero immersion specimens to determine initial fibre and fabric properties.

Immersion of Specimens

Containers were required which were chemically inert to the immersion fluids. Seamless glass tanks were used for the heavy oil because glass does not react with oil. Produced water often has a pH 10-12 and glass is known to be damaged by an alkaline environment. Polyethylene is inert to alkaline environments, therefore, polyethylene containers were chosen for the produced water and the distilled water. The specimens were suspended from a grid so that they did not touch the sides or bottom of the immersion tank. Glass lids were used to maintain a consistent environment in the immersion tanks. The temperature of the fluids ranged from 21°C to 24°C during the 120 day immersion period.

Heavy Oil

The heavy oil used in this study was a sweet crude oil supplied by Norcen Energy Resources Ltd., Provost, Alberta. The petroleum industry uses the term sweet to indicate that no sulphur is present in the oil. The sweet crude oil was a dark, brown-black colour with a strong tar odor. The viscosity of the oil was 8300 MPa·s at 23 °C and the specific gravity of the oil was 0.8 to 0.9 at 15 °C. The oil contained 75.31 % carbon, 10.59 % hydrogen, 10.19 % oxygen and 0.37 % nitrogen. The sulphur content was 2.56 % by weight. A small amount of unknown volatiles was present in the oil (Norcen Energy Resources Ltd., 1989).

Produced Water

A simulated produced water was prepared in the laboratory based on a typica water analysis of produced water from a heavy oil well in the Lloydminster area. Th water analysis was supplied by Norcen Energy Resources Ltd. The cations present were sodium (12066.9 mg/L), calcium (609.2 mg/L), magnesium (274.8 mg/L) and dissolved iron (3.3 mg/L) with 0.3 mg/L undissolved iron. The anions present were chloride (20208.2 mg/L), and bicarbonate (473.5 mg/L). The pH was 7.31 at 20.4 °C. Sodium chloride (11.4 g/L), calcium chloride (0.42 g/L), magnesium carbonate (0.51 g/L) and 10% concentrated hydrochloric acid (2.6 ml/L) were dissolved in distilled water to make simulated produced water. To ensure that small amounts of iron and other impurities were present in small quantities in the simulated produced water, commercial grades of salts were used, for example, the NaCl contained 2ppm iron and the $MgCO_3$, 0.001% iron. The pH of the simulated produced water ranged from 6.5 to 8.5 over the 120 day interval.

Cleaning of Specimens

To choose a solvent to clean the fabrics after immersion in the heavy oil, a preliminary test was completed to ensure there was no measurable chemical interaction between the cleaning solvent and the fibres as determined by change in fibre diameter. Specimens from each fabric were left in Varsol solvent for 24 hours and then removed to air dry. The comparison of fibre diameters before and after immersion in the heavy oil indicated there was no significant difference ($\alpha = 0.10$) in the mean fibre diameters ($n=20$) before and after immersion in Varsol (Appendix A-1). It was assumed from this test that the solvent could be used to remove the heavy oil without swelling the fibres. To determine if the solvent would clean the oil-immersed specimens, one specimen of each fabric was immersed in the heavy oil for 7 days then rinsed five times with solvent until all noticeable traces of oil had been removed. This cleaning procedure was used on all the specimens immersed in the heavy oil.

Laboratory Testing

The testing program for each immersion fluid (Table 5) shows which index tests were conducted at each immersion interval. This testing program was duplicated for three immersion fluids and three test fabrics. The number of measurements taken for each test is also shown.

Table 5

Measurements Recorded at Each Time Interval for Each Fabric Immersed in Each Fluid

Time (days)	Burst Test	Fibre Diameter	Mass & Thickness
0	10	50	10
15	0	50	0
30	10	0	0
60	10	0	0
120	10	50	0

Burst Testing

There are two main diaphragm bursting strength test methods, Can/CGSB 4.2-M77 Method 11.1 and ASTM D3786-80a). The diaphragm test methods are designed for knitted fabrics and have been adapted for nonwoven geotextiles. The apparatus consists of a base, a rubber diaphragm, metal ring and clamp (Figure 11).

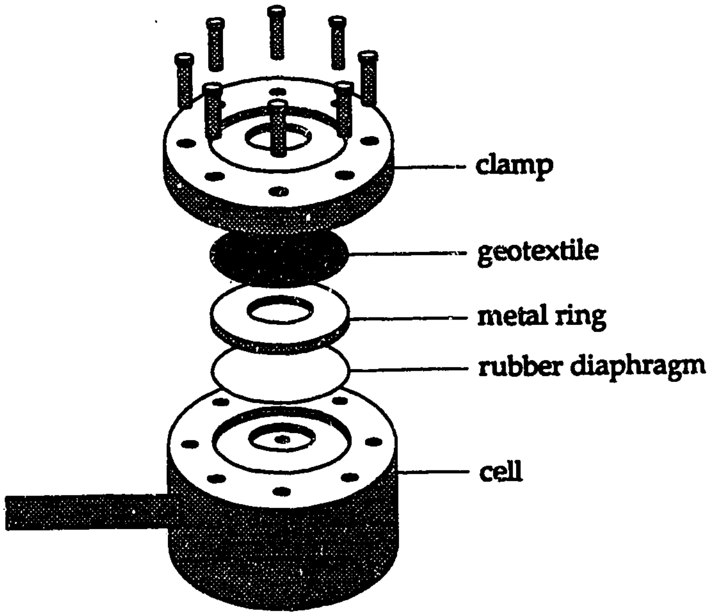
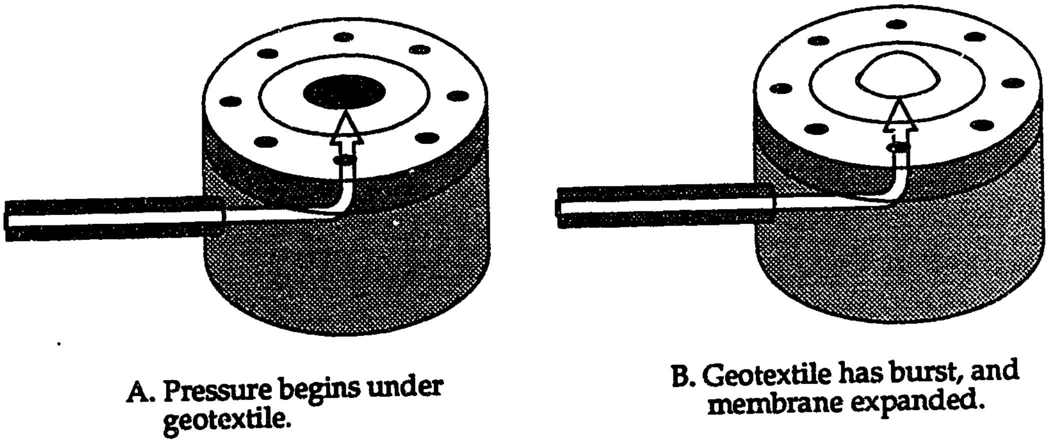


Figure 11 Burst Cell Apparatus

Fluid creates a pressure against the rubber diaphragm allowing it to extend. A metal ring is placed on top of the rubber diaphragm to hold the outer edges of the diaphragm in place. The fabric is placed on top of the metal ring and rubber diaphragm and a metal clamp holds the whole apparatus together. The liquid in the cell is pumped through the base to extend the diaphragm. The diaphragm extends radially until the fabric over it can no longer resist the stress and failure occurs (Figure 12). The Mullen Burst Tester is one type of diaphragm burst tester but it does not have the capacity to control the flow rate of the liquid which expands the rubber diaphragm.


A. Pressure begins under geotextile.

B. Geotextile has burst, and membrane expanded.

Figure 12. Pressure Applied in the Test Apparatus to Burst the Specimen

The burst cell used in this study was developed especially for geotextile testing. Figure 11 shows the structure of the cell. The flow rate used in this study was held at a constant rate of 78 ml/min. The ASTM D3786-80a test method uses equipment similiar to the cell developed for this study, therefore, it is an appropriate test procedure to follow for burst testing. In the ASTM test method D3786-80a, glycerine is the liquid used to extend the diaphragm, however, in this study water was used as the liquid. To achieve the high pressures required to break the specimens, nitrogen was pumped with the water. The pressure capacity of the burst cell is normally 10 MPa, however, the strength of the diaphragm limited the pressure of the burst cell to approximately 6 MPa. Burst testing was completed on dry specimens after 0, 30, 60 and 120 days of immersion.

Fabric Thickness and Mass Testing

Fabric thickness and mass were determined on unaged specimens under standard conditions (65% relative humidity and 20 °C) to determine initial characteristics. The Frazier Compressometer was used for fabric thickness measurements, following Can/CGSB-148.1 No.3-M85 test method, Thickness of Geotextiles. Mass was determined following test method Can/CGSB-148.1 No.2-M85, Mass per Unit Area.

Fibre Diameter Testing

The polarizing microscope with a calibrated eyepiece micrometer was used to measure fibre diameters after 0, 15, and 120 days of immersion. Fifty fibres for each time period were measured and the values were averaged to determine the mean fibre diameter. The mean fibre diameters after 15 and 120 days of immersion were compared with original fibre diameters to determine if swelling had occurred.

Scanning Electron Microscope

Longitudinal and cross sections made from specimens immersed in heavy oil for 120 days were examined using the Cambridge Stereoscan 250 Scanning Electron Microscope (SEM). An attempt was made to view longitudinal uncleaned oil-immersed specimens without a gold coating. The oil on the specimens was energized in the SEM so that it was difficult to focus on the fibres; therefore, all the longitudinal sections approximately 1 cm^2 were mounted on metal stems and sputter coated with gold film 100 to 150 angstroms thick. The oil-immersed specimens were cleaned with Varsol before gold coating. Examination of longitudinal sections was completed to observe changes in the fibre surface. Fibre diameter was compared with fibre diameter measurements recorded with the polarizing microscope. Swelling of the oil immersed specimens was observed and representative pictures were photographed. Various methods were used to make cross sections of fibres, such as ultramicrometry, where the fibre is embedded in a resin and a cross section 5 μm thick is cut. The resin must adhere to the fibre surface. Because synthetic fibres usually have a smooth surface this method was unsuccessful as the fibres slipped out of the various resin materials. The final method which was used in this study was the Shirley Plate Method. The specimens were packed into a hole in a metal plate with cellulose acetate packing yarns and cut flush with the plate surface with a razor. The plates were sputter coated with gold on one side before examination. The cross-sectional shape of the fibres was observed before and after immersion in the heavy oil. The fibre cross sections were also used for energy dispersive x-ray analysis (EDXA). The x-rays bombard the electrons in an atom and knock them out of position. EDXA was completed on the fibre that showed the greatest amount of swelling. Sulphur is a readily identifiable element that would probably be present if the oil was absorbed into the fibre. Gold and sulphur show up graphically in the same area on an EDXA chart so that to observe a sulphur peak the uncoated side of the cross section plate was used. This presented a difficulty in identifying the fibre cross section from the packing yarns, because the fibres became energized. For this reason, EDXA was not completed on the fibres that did not swell.

Statistical Analysis

An SPSSx one way analysis of variance was used to determine if there was a significant difference at $\alpha = 0.10$, between the burst strength before and after immersion for each fabric and a selected immersion fluid at a selected interval. Fibre diameters were also tested by a one way analysis of variance using time and fluid as independent variables. A Scheffe multiple range test ($\alpha = 0.10$) was used to determine which means were significantly different from one another. In cases where the Scheffe test was not sensitive enough to deterct whcih means differed, a Duncan's multiple range test was used. The three fabrics were compared using an ANOVA to determine if there was a significant difference at ($\alpha = 0.10$) in the burst strength and fibre diameter among the fabrics.

CHAPTER 4 RESULTS AND DISCUSSION

The purpose of this study was to determine the effects on the physical and mechanical properties of three geotextile filtration fabrics of exposure to heavy oil well fluids in the laboratory. Mass and thickness tests were completed to determine initial physical characteristics of the fabrics (Table 6). A mechanical test was required in which biaxial strain would be applied to the fabrics uniformly and approximate the pressure that fabrics may encounter in a heavy oil well; therefore, burst testing was selected as an appropriate laboratory test. Geotextile specimens were tested for change in burst strength after being immersed in distilled water, produced water and heavy oil for a maximum of 120 days. This test was used to indicate whether the strength of the filter fabrics was affected by long term immersion in well fluids. Change in fibre diameter measurements after 15 and 120 days immersion was used to evaluate whether the fibres swelled in any of the immersion fluids. Significant swelling could change the filtration characteristics of a nonwoven fabric. Scanning electron microscopy was completed to determine if there were surface changes to the fibres after immersion in oil well fluids. Comparison of fibre diameter measurements before and after immersion and visual examination of the fibres may indicate whether there was surface damage that could affect the mechanical properties of the fabrics. Energy Dispersive X-ray Analysis (EDXA) was completed on fibres that swelled in heavy oil. The fabric which exhibits the least amount of degradation after immersion in the heavy oil well fluids may be recommended for future filtration testing with heavy oil.

Table 6

Fibre and Fabric Properties Before Immersion in Heavy Oil Well Fluids

Property	P0820 (polypropylene)	Q200 (polyester)	TTNT (polyester)
Mass (g/m^2)	322	597	822
Thickness (mm)	3.02	4.24	2.54
Burst Strength (MPa)*	2.41	4.65	----
Grab Strength (N)*	890	1112	6400

* data from manufacturers' literature (test methods unknown)

Burst Test

Burst Test Results on P0820

Specimens of polypropylene P0820 manufactured by Exxon™ were immersed in distilled water, produced water and heavy oil. Ten specimens were burst tested at each interval (0, 30, 60, and 120 days). Values for mean burst strength (MPa) and standard deviation are recorded in Table 7. Raw burst strength results are presented in Appendix A-3.

The initial burst strength was 2.79 MPa. After 120 days immersion in distilled water, produced water and heavy oil the strength decreased by approximately 0.5 MPa or 15%. There was a significant difference in burst strength among the specimens immersed at different intervals in the distilled water and in the produced water. These results were unexpected because polypropylene is hydrophobic. Water does not interact with the polypropylene polymer because there are no polar groups. The high crystallinity and stereoregularity of polypropylene contribute to the chemical resistance of polypropylene. The Scheffe multiple range test indicates there was a significant difference in burst strength after 60 and 120 days immersion in both the water fluids. The pooled standard deviation was approximately 0.4 which would indicate that individual specimens were variable in burst strength. The loss of strength may be the result of inconsistency in the fabric during manufacturing. It is difficult to control the random laying of fibres in a web structure.

There was a significant difference ($\alpha = 0.10$) in mean burst strength after immersion in heavy oil. The strength decreased by 0.47 MPa or 17 % after 120 days of immersion. This result was expected because polypropylene is oleophilic or oil loving. The solubility parameters of polypropylene are 8.1 and 9.2-9.4 $cal^{0.5}cm^{-1.5}$ and components of heavy oil such as aromatic or aliphatic hydrocarbons have solubility parameters of about 6.7 to 9.2 $cal^{0.5}cm^{-1.5}$. If two solubility parameters differ by ± 3.4 $cal^{0.5}cm^{-1.5}$ the liquids and/or fibres are likely to interact with one another.

Table 7

Burst Strength After Immersion in Well Fluids

Fabric	Time (days)	Mean Burst Strength (MPa) and (Standard Deviation) in: Distilled Water*	Produced Water**	Heavy Oil***
P0820	0	2.79 (0.32)	2.79 (0.32)	2.79 (0.32)
	30	2.59 (0.41)	2.68 (0.40)	2.62 (0.54)
	60	2.19 (0.41)	2.30 (0.26)	2.44 (0.39)
	120	2.29 (0.34)	2.28 (0.54)	2.32 (0.31)
Q200	0	3.32 (0.17)	3.32 (0.17)	3.32 (0.17)
	30	3.77 (0.23)	4.20 (0.39)	3.49 (0.52)
	60	3.17 (0.17)	3.00 (0.17)	3.20 (0.29)
	120	2.76 (0.16)	3.17 (0.34)	3.33 (0.34)
200/50 TTNT	0	>6.33 (0.82)	>6.33 (0.82)	>6.33 (0.82)
	30	>6.33 (0.82)	>6.33 (0.82)	>6.33 (0.82)
	60	>6.33 (0.82)	>6.33 (0.82)	>6.33 (0.82)
	120	>6.33 (0.82)	>6.33 (0.82)	>6.33 (0.82)

* pooled standard deviation after immersion in distilled water: P0820 = 0.43 MPa, Q200 = 0.183 MPa

** pooled standard deviation after immersion in produced water: P0820 = 0.440 MPa, Q200 = 0.545 MPa,

*** pooled standard deviation after immersion in heavy oil: P0820 = 0.434 MPa, Q200 = 0.355 MPa,

Burst Test Results on Q200

Specimens of polyester Q200 ™ manufactured by Wellman Quline Inc., were immersed in distilled water, produced water, and heavy oil for 0, 30, 60 and 120 days. The mean burst strength of the fabric was 3.32 ± 0.17 MPa before immersion in fluids. After 120 days of immersion in heavy oil, the burst strength did not change, however, the fabric immersed in distilled water was 0.56 MPa or 17% weaker and in the produced water, was 0.15 MPa or 4% weaker than the intital strength of the fabric. (Table 7). Raw burst strength data is recorded in Appendix A-3.

The significant change in strength ($\alpha = 0.10$) of Q200 after immersion in distilled water and produced water for 30, 60 and 120 days is difficult to explain. Q200 is composed of polyester fibres which exhibit hydrophobic characteristics. The solubility parameters of distilled water ($\delta = 23.2$ cal$^{0.5}$cm$^{-1.5}$) and polyester ($\delta = 9.8$ and 12.1 cal$^{0.5}$cm$^{-1.5}$) are not within the same range, therefore, it would not be expected that these fluids would be absorbed and cause changes in the strength of the fibre. Water is a polar solvent and polyester is nonpolar, therefore, interaction of the water and the fibre is unlikely. Q200 may have shown a significant change in burst strength due to the variability in the nonwoven fabric structure. During the manufacturing process, it is difficult to control the laying of fibres on the conveyor belt as the fabric web is assembled. For the fabric immersed in the distilled water the Scheffe Multiple Range Test indicated there was a significant change in mean burst strength of specimens at each time interval. The burst strength of specimens immersed for 0 and 60 days formed a homogenous subset. The burst strength of the 30 day produced water immersion specimens (4.20 MPa) was significantly higher than the control (3.32 MPa). The standard deviation of Q200 specimens immersed for 30 days in oil, distilled water and produced water were relatively high ranging from 0.2 to 0.5 MPa.The high standard deviation may indicate that the results after 30 days immersion were skewed due to fabric variability or inconsistency in the test apparatus. The pH of the produced water was neutral so that the solubility parameter of the produced water would probably be close to that of distilled water, therefore, interaction with the fibres would be unlikely. The mean burst strengths of specimens immersed in heavy oil for 0, 30, 60, and 120 days were not significantly different ($\alpha = 0.10$).

Burst Test results on 200/50 TTNT

Specimens of polyester 200/50 TTNT (here after TTNT) manufactured by Rhone Poulenc Inc. were immersed in distilled water, produced water and heavy oil for 0, 30, 60 and 120 days. The burst testing apparatus did not have sufficient capacity to rupture this high strength fabric. The stitchbonded scrim attached to the web structure reinforced the geotextile so that the extensible membrane in the burst cell could not exert enough pressure on the fabric to burst the specimen. The results recorded in Table 7 reflect the maximum amount of pressure the membrane could exert on the fabric before the membrane failed. The actual burst strength of this fabric is greater than the results shown in Table 7. The raw burst strength data are recorded in Appendix A-3. The trade literature did not indicate burst and puncture strength which suggests that equipment used for this type of test was not available to the manufacturer. The mean burst strengths that were recorded, however, are useful in determining the consistency of the fabric construction. It can be concluded from the range of values that the burst strength of the TTNT, at a very minimum, is greater than 6.33 MPa at all immersion periods.

The burst equipment was developed to exert pressures to 10 MPa, however, the membrane material which was used for testing was incapable of withstanding these pressures. The membrane is required to be flexible to expand under pressure, but at a pressure below 10 MPa the membrane reached its maximum extensibility and ruptured. Stronger membranes were tested so that higher pressures could be achieved. The stronger membranes had less extensibility which caused problems with fluid leakage at increased pressures. McClung (1988) stated that the minimum strength of a well filter fabric must be between 1 to 2 MPa to withstand sand pressure in a down hole oil well. TTNT exceeds this requirement of strength by at least 200%. Further comparison of the strength of the TTNT fabrics can not be made since the measurements are only a minimum strength value.

Comparison of Burst Test Results Among Three Geotextiles

McClung (1988) selected potential well filter fabrics for testing based on strength and durability criteria reported by manufacturers. The fabrics in this study were laboratory tested to evaluate burst strength and determine which fabric will be most suitable for a filtration fabric in a heavy oil well. The fabrics are required to withstand sand pressure of 1 to 2 MPa in a heavy oil well over a long period of time, therefore, it is necessary that the fibres do not degrade or weaken in the heavy oil fluids. The burst strength of the three fabrics varied significantly. The P0820 had the lowest burst strength at 2.79 MPa before immersion in the test fluids. The Q200 geotextile had a burst strength of 3.32 MPa and the TTNT geotextile had the highest burst strength of greater than 6.33 MPa before immersion in the test fluids. All three fabrics have an initial strength well above that required by a fabric used in a well filter. The difference in mean burst strength before immersion in the test fluids can be explained by the physical properties of the fabrics. The construction of the TTNT may explain why it exhibited a much higher burst strength than the other two geotextiles. TTNT is made of a web structure with warp and weft yarns stitch bonded to it. The Q200 was a thicker fabric than the P0820, thus there are more fibres present to create a higher strength. The weakest link theory states that the strength of a fabric is equal to the strength of the shortest yarn (Pierce, 1926). The pressure exerted on the membrane was borne by the surrounding fibres in the nonwoven fabric. The P0820 fibres withstood pressure to 2.79 MPa, but at this pressure the fibres slide past one another, lowering the strength and causing the fabric to burst.

Due to the high variability in the burst strength of the fabrics prior to immersion in the test fluids, it is difficult to compare the burst strength of the fabrics after immersion in the distilled water, produced water and heavy oil. A useful comparison may be the percent change in the burst strength of the fabrics (Table 8).

Table 8

Percent Change in Burst Strength

Fabric	Change in Burst Strength (%) after 120 days immersion in: Distilled Water	Produced Water	Heavy Oil
Q200	- 17	- 5	0
TTNT	+ 2	+ 0	+ 12
P0820	- 18	- 18	- 17

+ = gain in strength
- = loss in strength

The fabric with the greatest overall loss in strength after 120 days of immersion was P0820 at 18 %. The Q200 fabric lost 17 % of its initial strength after immersion for 120 days in the distilled water but remained relatively stable in the produced water and heavy oil. Although all three fabrics are recommended for filtration based on strength criteria, one must consider the amount of time it would take for a fabric to burst at a value below 2 MPa, the minimum suggested strength for a filter fabric.

The results after 30 days of immersion in the well fluids appear to be skewed; all the tests indicated a higher burst strength. All the tests were completed within a day of each other, therefore, if the test apparatus was not functioning properly, all the tests would reflect the same error. The 30 day results were omitted from Figures 13 and 14 to calculate the equation of the line joining the burst strength results. It appears that the plot of burst strength versus immersion time is linear. If the linear regression line is extrapolated, the burst strength of the polyester Q200 will decrease to 2 MPa after 990 days of immersion in produced water. The polypropylene P0820 would reach 2 MPa after 191 days immersion in heavy oil and after 228 days of immersion in the produced water. Based on the above considerations and the need for the oil well filter to be efficient for an extended time, the fabrics likely to remain durable are the Q200 and TTNT fabrics.

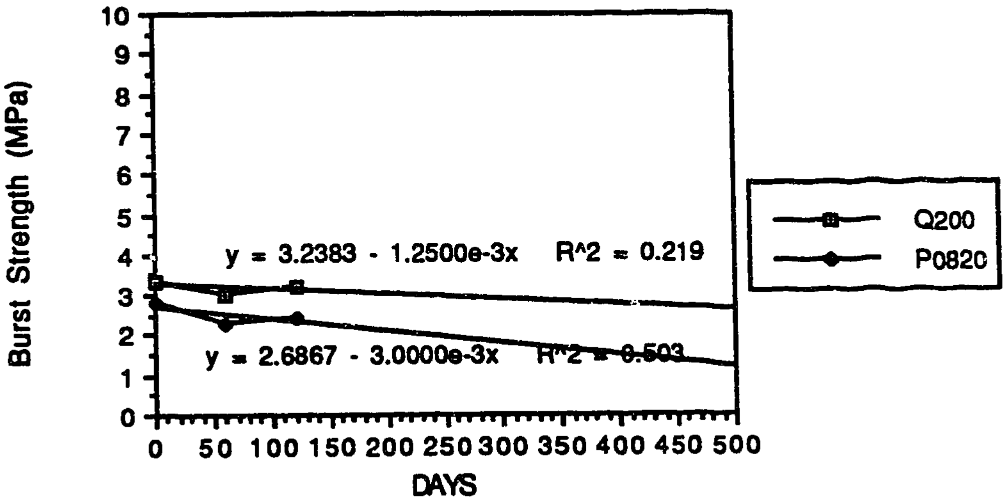


Figure 13 Linear Regression of Burst Strength (MPa) after Immersion in Produced Water

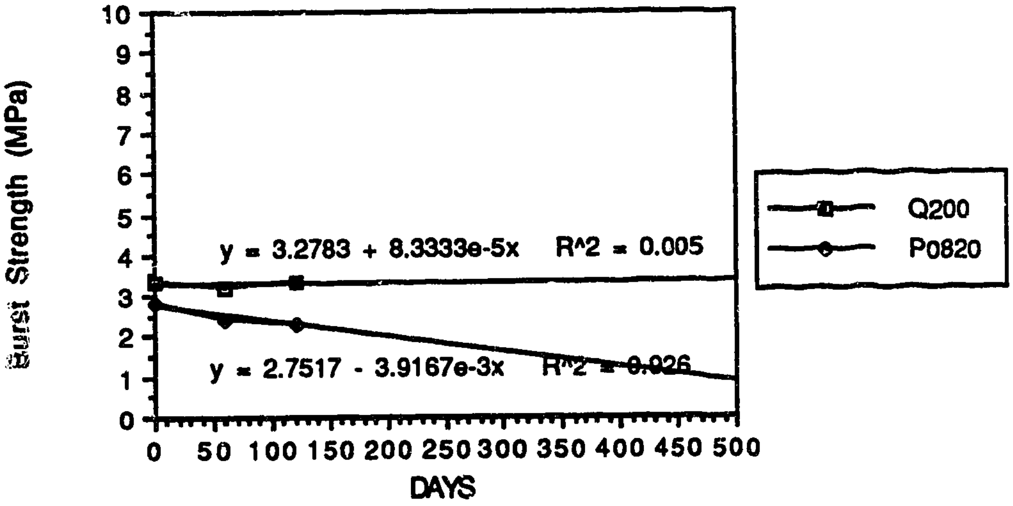


Figure 14 Linear Regression of Burst Strength (MPa) after Immersion in Heavy Oil

Fibre Diameter

Fibre Diameter Results on P0820

The P0820 fabric made from polypropylene did not show significant swelling ($\alpha = 0.10$) after immersion in distilled water or produced water for 120 days (Table 9). This result is not surprising because polypropylene is a nonpolar polymer which does not attract polar solvents like water. The solubility parameter of water ($\delta = 23.2$) is not within the solubility parameter range of polypropylene ($\delta = 8.1$ and 9.2-9.4) therefore, interaction of the water with the polymer is unlikely.

Heavy oil contains nonpolar aliphatic and aromatic hydrocarbons which have solubility parameters close to those of polypropylene, thus, some swelling of the fibres in oil was expected. After 120 days of immersion in heavy oil, the polypropylene fibres showed a significant difference in fibre diameter ($\alpha = 0.10$) (Appendix A-4). The mean diameter of 50 fibres increased from 24.9 ($\sigma = 5.82$) to 29.4 µm ($\sigma = .64$) which is an 18% increase in diameter. After 120 days of immersion, it was evident from microscopic examination of the fibres that the swelling that did occur was localized and swelling did not occur along the entire length of the fibre. This amount of swelling may alter filtration properties because the spaces between the fibres may be significantly smaller. The fact that the mean fibre diameters were not significantly different after 15 days of immersion in heavy oil, suggests that swelling did not occur early in the test interval but rather over an extended time period. Vittoria and Riva (1986) immersed polypropylene fibres in various solvents to determine the amount of swelling that would occur during a 10 day time span(see Table 4). It was concluded that swelling occurred in the first 24 hours and reached equilbrium after 10 days. The results from this study indicate that an equilibrium in swelling was not reached in 15 days and it is unknown whether the swelling reached equilbrium after 120 days.

Table 9

Fibre Diameter After Immersion in Well Fluids

Fabric	Time (Days)	Mean Fibre Diameter (µm) and (Standard Deviation) in: Distilled Water *	Produced Water**	Heavy Oil ***
P0820	0	24.9 (5.82)	24.9 (5.82)	24.9 (5.82)
	15	26.3 (5.08)	25.6 (4.21)	24.2 (3.48)
	120	25.8 (5.97)	25.6 (4.52)	29.4 (6.64)
Q200	0	29.7 (2.10)	29.7 (2.10)	29.7 (2.10)
	15	28.6 (3.41)	30.4 (2.77)	30.5 (3.57)
	120	29.3 (2.82)	28.5 (3.05)	31.4 (4.60)
200/50 TINT(grey)	0	24.0 (2.43)	24.0 (2.43)	24.0 (2.43)
	15	23.3 (1.99)	23.9 (2.37)	23.3 (1.98)
	120	23.3 (2.21)	23.7 (1.90)	23.7 (2.16)
200/50 TINT (white)	0	21.7 (1.40)	21.7 (1.40)	21.7 (1.40)
	15	19.9 (1.03)	20.2 (1.91)	20.1 (1.13)
	120	22.7 (0.98)	20.5 (1.47)	21.4 (1.43)

* pooled standard deviation after immersion in distilled water: P0820 = 5.625 µm, Q200 = 2.853 µm, TINTwhite = 1.654 µm, TINTgrey = 2.233 µm.

** pooled standard deviation after immersion in produced water: P0820 = 4.877 µm, Q200 = 2.772 µm, TINTwhite = 1.735 µm, TINTgrey = 2.234 µm.

*** pooled standard deviation after immersion in heavy oil: P0820 = 5.481µm, Q200 = 3.619 µm, TINTwhite = 1.492 µm, TINTgrey = 2.201 µm.

Fibre Diameter Results on Q200

Changes in fibre diameter after immersion in the well fluids are shown in Table 9. Groups which showed significant differences (α= 0.10) in diameter are also shown in Appendix B. The initial fibre diameter of the Q200 polyester fibres was 29.7 µm (σ= 2.10). There was no significant difference in fibre diameter that is, no swelling after 15 or 120 days immersion in distilled water. Between 15 and 120 days of immersion in produced water there was a significant difference in fibre diameter. At 15 days the fibres were swollen 2.4% and at 120 days the mean fibre diameter had decreased 4%, thus the total change in diameter was 6.4 %. It is unlikely this change will affect filtration properties. Neither shrinkage nor swelling in produced water was expected because of the large difference in solubility parameters. The polar water molecules do not interact with the nonpolar polyester molecules. The initial standard deviation was 2.10 which encompasses the mean at 15 days (30.4 μm) and at 120 days (28.5 μm) so that in reality the fibres did not shrink or swell in the fluid. It was expected that the fibres would be variable, therefore, at each interval 50 measurements were observed on different fibres and the mean fibre diameter was calculated to compare the groups. The variability in fibre diameter may be a result of the drawing stage in manufacturing. Fibres are placed under tension during drawing and if the temperature at which the fibres is cooled varied or the tension is varied, the fibre diameter will be inconsistent. Generally, nonwoven fabrics are usually manufactured by the cheapest processes available, thus, quality control is often limited.

Q200 fibres immersed in heavy oil for 120 days were significantly different in diameter from the original specimens, having swollen 5.7%. This is considered a minimal change in fibre diameter. The solubility parameters of some components of heavy oil are close to the solubility parameters of polyester. It was predicted that some swelling of the polyester fibres would occur.

Fibre Diameter Results on 200/50 TTNT

The TTNT was composed of two different polyester fibres. The base of the fabric was a random web made of grey filament fibres, which were consolidated by needlepunching (hereafter TTNT grey) while the scrim was made of white filaments (hereafter TTNT white) laid on the web at right angles and stitchbonded to it. Both grey and white filaments were immersed in the test fluids. After immersion in the distilled water the TTNT white fibres were significantly different ($\alpha = 0.10$) in diameter at each interval. It appears that the fibres shrank 8% after 15 days immersion and then swelled 14% after 120 days immersion. There was no significant difference in mean fibre diameter for TTNT grey fibres, which was expected.

After immersion in produced water for 15 days the mean diameter of the TTNT white fibres was significantly different from the original fibre diameter. The mean fibre diameter decreased by 7% after 15 days immersion. There was no significant difference between the fibres immersed for 15 and 120 days. The original mean diameter of TTNT grey fibres was 24 μm and did not change significantly different after immersion in the produced water.

The same trend followed with fibres immersed in heavy oil. The TTNT white fibre diameters were significantly different after 15 days immersion; the fibres shrank from 21.7 to 20.1, a 7% decrease. There was not a significant difference between fibre diameters between 15 and 120 days immersion. The final diameter change during 120 days of immersion in oil was 0.3 µm. This indicates that swelling occurred in the first 15 day interval but no significant changes occurred after that time interval. The TTNT grey also followed the same trend of showing no significant difference in mean fibre diameter after immersion in heavy oil. The TTNT grey fibres formed the web structure of the fabric. The permittivity or cross plane permeability of the fabric is dependent on the spaces between the TTNT grey fibres while the TTNT white contributes to the strength and transmissivity or inplane permeability of the fabric. Since the mean diameter of the TTNT grey fibres did not change significantly in the oil well fluids it can be concluded that the permittivity of the fabric will not be affected by change in fibre diameter. In reality, the change in mean diameter of TTNT white fibres will not influence the filtration properties of the fabric since its main function is to increase the strength of the fabric.

Comparison of Fibre Diameter Test Results Among Three Geotextiles

The polyester and polypropylene fibres used in the three filter fabrics had diameters typical of most textile fibres, that is, 20 to 30 µm. Although there was a significant statistical difference, the actual diameter changes were very small. There was a significant difference in fibre diameter among the three fabrics before immersion in the test fluids, therefore, it is not meaningful to compare fibre diameters among the three fabrics after immersion, however, comparison of percent changes in fibre diameter are useful for determining which fibre showed the least amount of swelling (Table 10).

Table 10

Percent Change in Fibre Diameter after Immersion in Well Fluids

Fabric	Change in Fibre Diameter (%) after 120 days immersion in: Distilled Water	Produced Water	Heavy Oil
P0820 (polypropylene)	+3.6	+2.8	+18
Q200 (PET)	- 1.3	- 4.0	+ 5.7
TTNT grey (PET)	- 2.9	- 1.3	- 1.3
TTNT white (PET)	+4.6	- 5.5	- 1.4

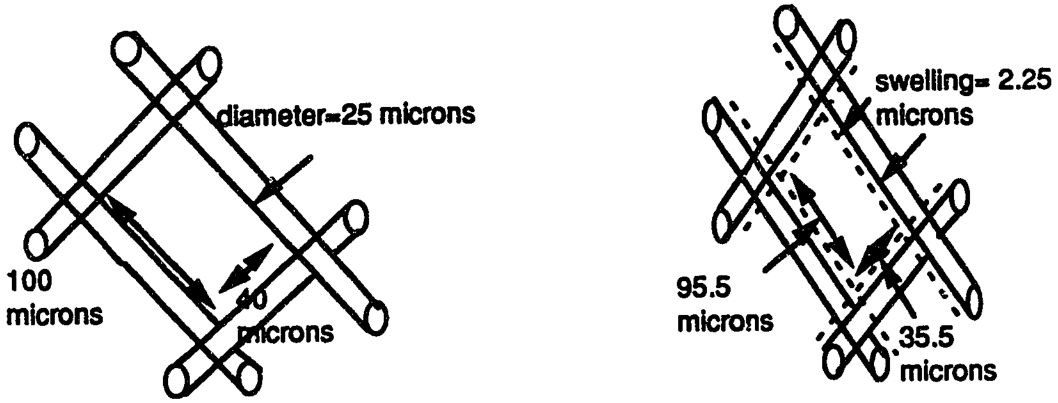
\+ = gain in strength
\- = loss in strength

The fibre that swelled the most was the P0820 (18%), followed by Q200 which increased by 5.7 % after 120 days immersion in the heavy oil. The TTNT fibres decreased in fibre diameter by approximately 1.3%. It was expected that the fibres would change the most in the heavy oil due to the similar nonpolar bonds of the molecules in the heavy oil and the fibres. It was also expected that the P0820 would have the greatest change since both of its solubility parameters are close to the components found in heavy oil. This would support Rusznak's (1983) conclusion that aliphatic and aromatic hydrocarbons will act like a swelling agent on polypropylene fibres. Polyester has two solubility parameters but only the aliphatic solubility parameter (9.8) is close to the solubility parameters of typical molecules in heavy oil, therefore, less swelling was expected in the polyester fibres.

The filtration properties of the fabric may be affected even at 18 % swelling. Fibres in a nonwoven web overlap each other which allows the fabric to perform as a filter. The spaces between the fibres range from 40 µm to 100 µm. If a fibre were to swell 18 % in diameter or 4.5 µm, such as P0820 fibres did, the decrease in space between the fibres may significantly affect the permeability of the fabric. Assuming the volume between the fibres is a three-dimensional space 40 X 100 X 25 µm (the thickness of an average fibre), the volume of the space would be 100,000 μm^3 (see figure 15). The fibre with a diameter of 25 µm, which swells by 18 % will increase in radius by 2.25 µm. The new volume between the fibres after swelling would be 35.5 X 95.5 X 25 or 84,756.25 μm^3. This represents a 15 % decrease in volume. The Kozeny-Poiseville equation shown below relates change in permeability to volumetric strain and porosity (Mitchell, 1976). The Kozeny-Poiseville model assumes that the flow of the liquid is laminar and the pore size is uniform. The decrease in volume of 15 % is considered the volumetric strain, that is, $\varepsilon_v = -0.15$, and the porosity at zero confining stress is 0.75 (Kerr et al, 1990, p.35). Using the Kozeny-Poiseville equation, the decrease in permeability is 40 %. A 40 % decrease in permeability may be misleading because the 15 % decrease in volume does not take into consideration that the fibres take one-third of the volume. A conservative volumetric strain would be .15 X 1/3 or 5 %. If 5 % is used in this equation the decrease in permeability would be 15 %

$$\frac{K' - K}{K} = \left(\frac{1+3\frac{\varepsilon v}{\emptyset} + \frac{3\varepsilon v^2}{\emptyset^2} + \frac{\varepsilon v^3}{\emptyset^3}}{1+\varepsilon v} \right) - 1$$

where:
K' = new permeability
K = initial permeability
εv= volumetric strain
$\emptyset$ = porosity
(Mitchell, 1976)



(before fibre swelling)

(after fibre swelling)

Figure 15 Schematic Model for Decrease in Permeability of Nonwoven Geotextile after Immersion in Heavy Oil

It is uncertain if the fibres had reached a swelling equilbrium after 120 days of immersion, therefore, based on the data from this study the efficiency of the filter can not be predicted conclusively. In conjunction with the results found by Kerr et al (1990), who tested these fabrics for permeability to oil, and found that the permeability of the P0820 was lower, it may be suggested that fibre swelling may affect the permeability of P0820. On the other hand, the TTNT fibres did not swell but shrank in the heavy oil and produced water. Fibres will swell during degradation and only after extensive damage has occurred, will they shrink. Although the shrinkage was not significant it is an unexpected result. Weigmann (1983) stated that shrinkage occurs as a result, of molecular relaxation or orientational strains in the direction of the principal orientation axis. Molecular relaxation involves substantial movement of polymer segments at temperatures above the polymer glass transition temperature. The glass transition temperautre of polyester is 90°C (Venkatesh, Khan, Bose, & Madan, 1980).

For shrinkage to occur, a solvent must diffuse into the amorphous regions of the fibre structure and must lower the glass transition temperature. Diffusion of the solvent is dependent on the solubility parameters of the solvent and the polymer. Venkatesh (1980) examined the shrinkage of polyester and concluded that solvents such as water, primary alcohols, aliphatic and aromatic hydrocarbons have little or no effect in the dimensional properties of polyester to 80°C. If the TTNT had been damaged to this extent it would have lost considerable strength and the burst test results would have indicated that the fibres were unstable. It is relatively safe to conclude that TTNT was not severely degraded in the heavy oil. The apparent shrinkage of the TTNT fibres can be explained simply by taking into consideration the variability in the fibres. All the TTNT fibre diameter measurements are within a 95 % confidence interval of the mean, therefore, changes in fibre diameter are due to variability in manufacturing rather than physical change due to immersion in the test fluid.

Scanning Electron Microscopy Examination

The Scanning Electron Microscope (SEM) was used to observe fibre surface characteristics and fibre cross-sections before and after immersion in heavy oil and to show visually the changes that occurred to the fibre surface and cross section. Energy Dispersive X-ray Analysis (EDXA) was completed to determine if elements present in oil were present in the interior of the P0820 fibres. It was expected that the heavy oil would be most readily absorbed by these fibres and they swelled the most after long term immersion. Heavy oil contains aliphatic and aromatic hydrocarbons which have solubility parameters close to those of polyester and polypropylene.

The surface of the of P0820 fibres before immersion in the heavy oil was smooth with striations (Plate 1). The striations are the result of the manufacturing process, when the fibres were drawn after extrusion from the spinneret. Striations on the surface of the cleaned fibres that had been immersed in heavy oil for 120 days are not readily apparent (Plate 2). This may indicate that the oil was absorbed on surface of the fibre. Plate 2 shows fibres that were immersed in heavy oil and had localized swelling. It was expected that the polypropylene fibres would swell in the oil, however, it was not anticipated that the swelling would be localized along the fibre axis. The amorphous regions in the fibre are the sites where the oil is absorbed. Usually, when a fibre swells , the swelling is uniform along the fibre axis. The localized swelling may be the result of surface degradation which may not be uniform along the fibre surface. The P0820 cross section was circular before and after immersion in the heavy oil (Plates 3 & 4). After immersion in the heavy oil, the fibre shape was distorted by the packing yarns. The fibres were spongy after immersion in the heavy oil so that distortion of the fibre shape could occur. The cross sections were used to complete EDXA (Appendix A-5). The cross section before immersion in the heavy oil showed a peak for gold, which was from the gold coating. After immersion in the heavy oil, the EDXA was completed on fibres without a gold coating so that the sulphur peak, which is close to the gold peak, could be observed clearly. Sulphur, silicon, potassium, chlorine, iron, calcium and chromium were all present in the cross section of the P0820. This indicates that the oil was absorbed into the fibre. It was not possible to determine how far the oil penetrated the fibres.

The polyester Q200 and TTNT longitudinal sections indicate that these fibres had slight striations before immersion in the heavy oil (Plates 5, 9, 13). After immersion in the heavy oil, it was observed that the Q200 surface was slightly etched (Plate 6). This may indicate that the fibre surface was affected by the oil, however, it did not significantly change the properties of the fibres. The TTNT fibres showed no change in surface appearance (Plates 10 & 14) after immersion in heavy oil. Fibre cross sections of the Q200 (7 & 8) and TTNT (11,12,15 & 16) were circular and showed no change in appearance after immersion in the heavy oil.

Plate 17 shows the random arrangement of fibres in the nonwoven web. The spaces between the fibres were much larger than the diameters of the fibres. Plate 17 also shows the variability of fibre diameter in the fabric. The standard deviation of the P0820 fibre diameter results indicate there was up to a 7 µm variability in fibre diameters. The P0820 fibres were randomly laid with very little orientation within the fabric structure (Plate 18). In the polyester Q200 fabric (plate 19) the fibres appeared to be more uniform in diameter and orientation through out the fabric structure. The fibres were more oriented, or parallel to one another than the P0820 fibres (Plate 20). The grey TTNT fibres (Plates 21 & 22) in the web were more uniform in diameter than the P0820 fibres and oriented like the Q200 fibres. The white TTNT fibres (Plates 9 & 12) were uniform in fibre diameter and stitched onto the web structure.

The lay of fibres in a fabric will affect the strength of the fabric. The P0820 exhibited the lowest strength of all three fabrics. It also had the most random arrangement of fibres in the fabric. The more transverse the fibres are in the fabric, the less strength the fabric will exhibit. The P0820 fibres may have been randomly laid beyond the maximum obliqueness point of strength. Therefore, in the Q200 fabric where the fibres were randomly laid, but more parallel than the P0820 the strength was higher.

The holes where the barbed needles entered the fabric during needle punching also contribute to the permeability of the fabric. The spaces made by the needle barbs between the fibres provide another channel for the oil to flow through the fabric. The spaces must remain relatively large compared to the fibre diameter to facilitate the filtration process. In plates 17, 19 and [illegible] the spaces between the randomly laid fibres can readily be seen. The spaces between the fibres are approximately five times the diameter of the fibres. If the fibres swell by 18 % in a heavy oil fluid, the space between the fibres would decrease by approximately the same amount, which may affect the filtration properties of the fabric.

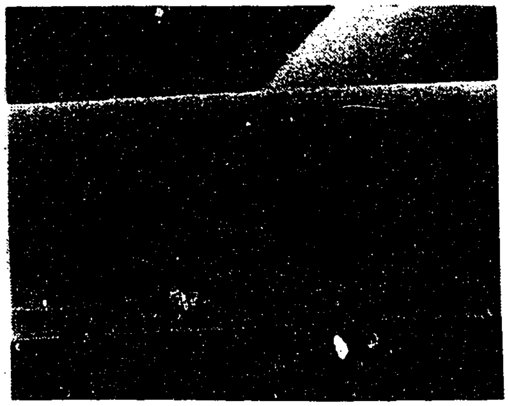


Plate 1 - Longitudinal section of P0820
before immersion in heavy oil
(magn. 1300x)

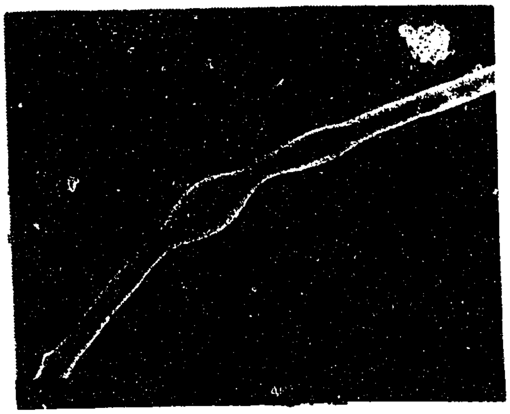


Plate 2 - Longitudinal section of P0820
after immersion in heavy oil
(magn. 10x)

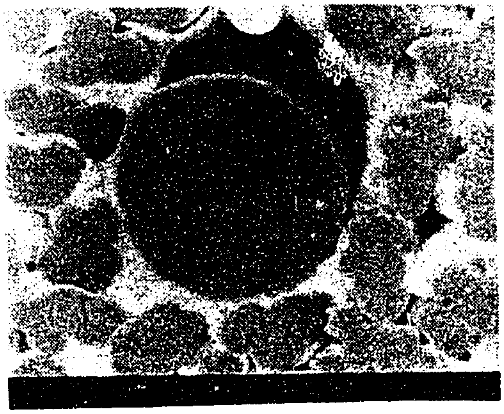


Plate 3 - Cross section of P0820
before immersion in heavy oil
(magn. 600x)

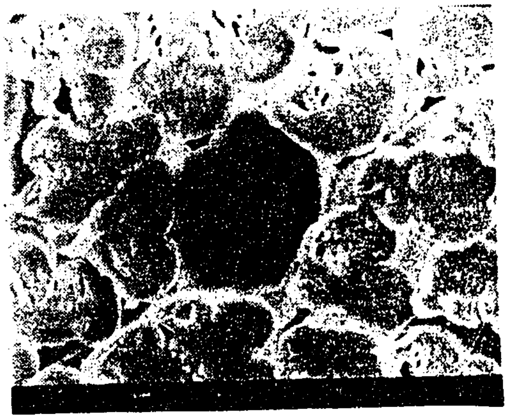


Plate 4 - Cross section of P0820
after immersion in heavy oil
(magn. 70x)

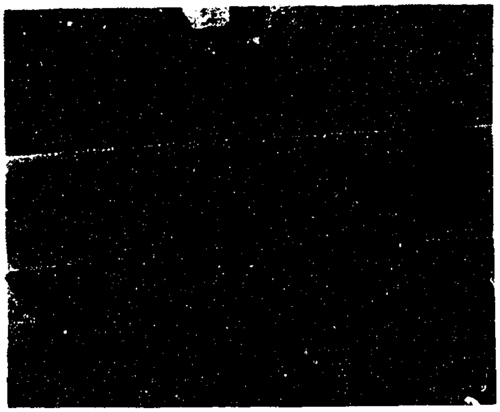


Plate 5 - Longitudinal section of Q200
before immersion in heavy oil
((magn. 50x)

Plate 6- Longitudinal section of Q200
after immersion in heavy oil
(magn. 50)

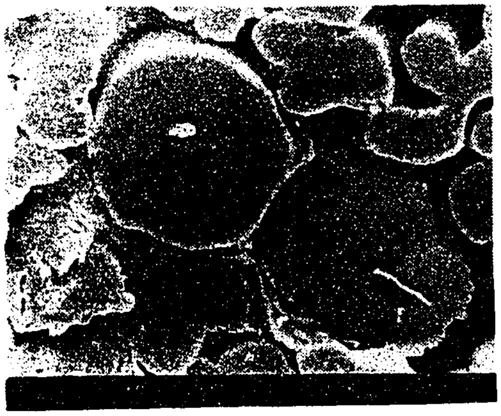


Plate 7 - Cross section of Q200
before immersion in heavy oil
(magn. 70x)

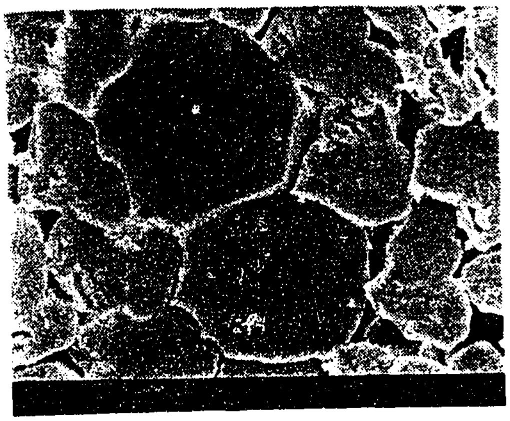


Plate 8 - Cross section of Q200
after immersion in heavy oil
(magn. 70x)

Plate 9- Longitudinal section of TTNT white before immersion in heavy oil (magn. 50x)

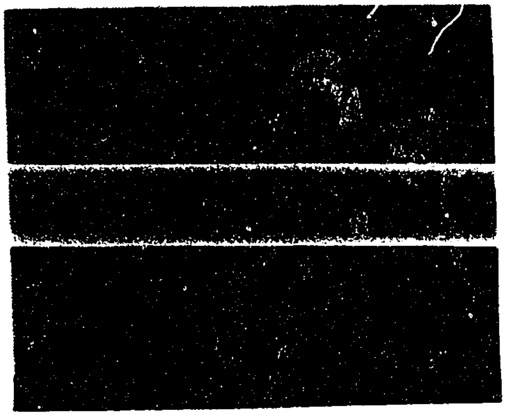


Plate 10 - Longitudinal section of TTNTwhite after immersion in heavy oil (magn. 50x)

Plate 11 - Cross section of TTNT white before immersion in heavy oil (magn. 70x)

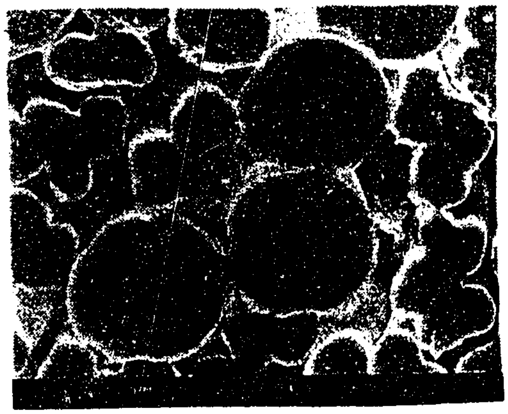


Plate 12 - Cross section of TTNT white after immersion in heavy oil (magn. 70x)

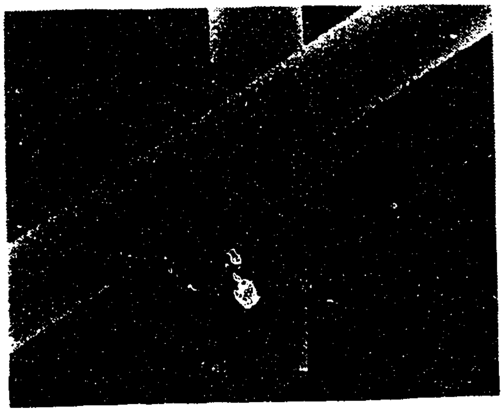


Plate 13- Longitudinal section of TINT grey before immersion in heavy oil (magn. 450x)

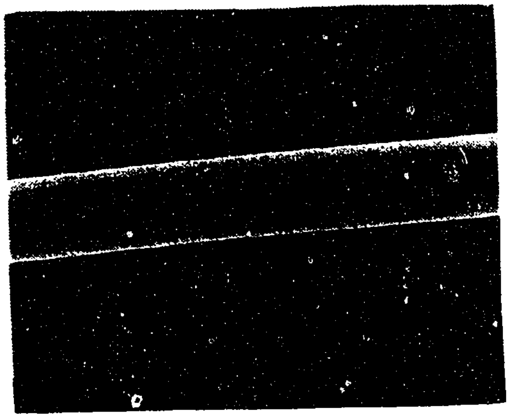


Plate 14- Longitudinal section of TINT grey after immersion in heavy oil (magn. 450x)

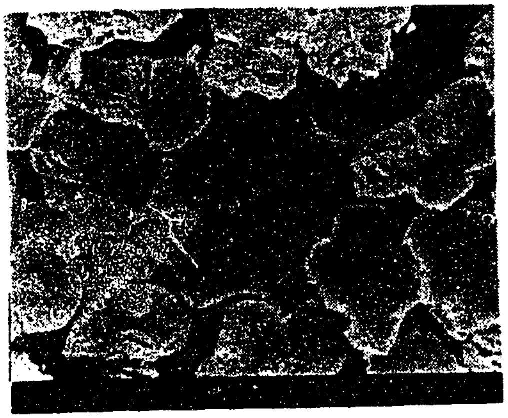


Plate 15 - Cross section of TINT grey before immersion in heavy oil (magn. 70x)

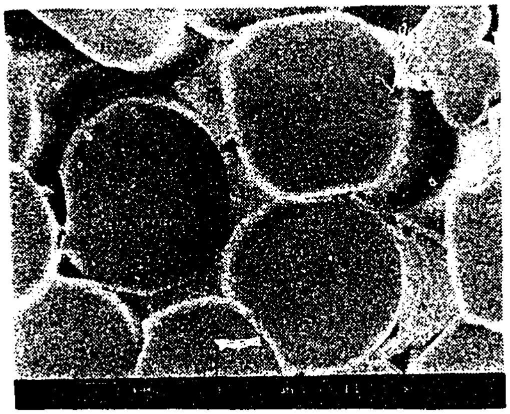


Plate 16 - Cross section of TINT grey after immersion in heavy oil (magn. 70x)

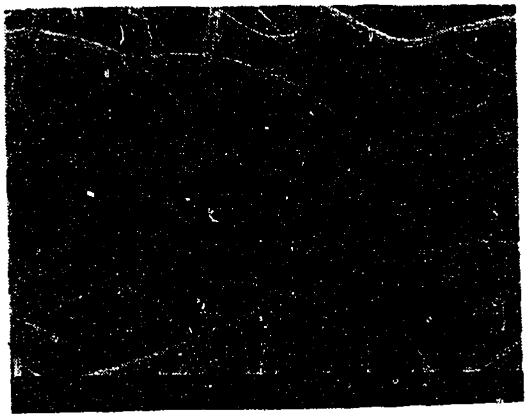


Plate 17- Random arrangement of P0820 fibres
((magn. 50x)

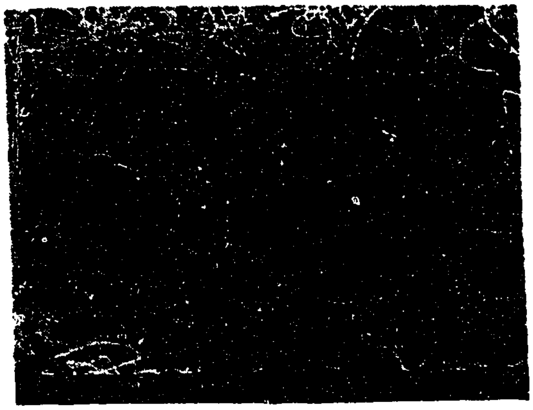


Plate 18 - Random arrangement of P0820 fibres
(magn. 10x)

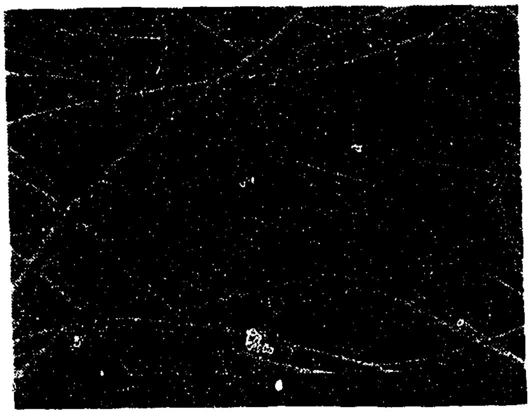


Plate 19- Random arrangement of Q200fibres
(magn. 50x)

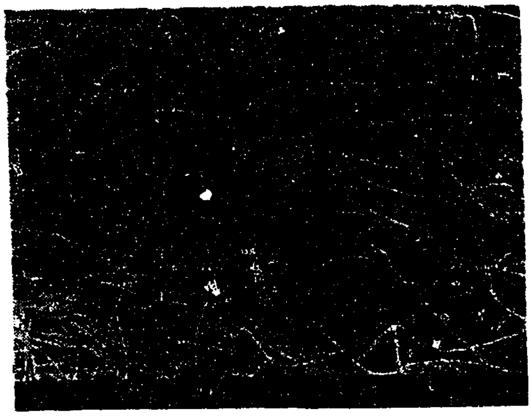


Plate 20 - Random arrangement of Q200fibres
(magn. 10x)

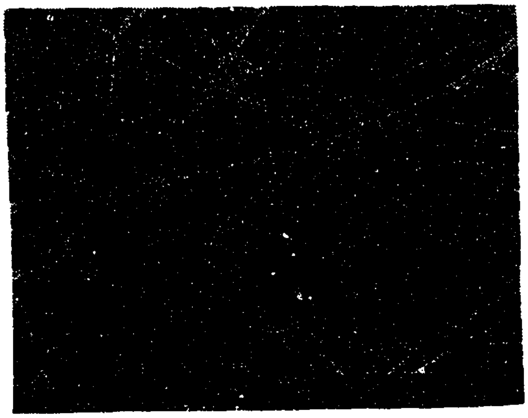


Plate 21- Random arrangement of TTNT
grey fibres
(magn. 50x)

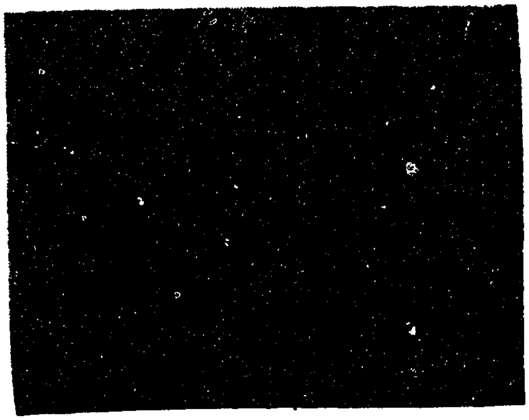


Plate 22 - Random arrangement of TTNT
grey fibres
(magn. 10x)

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

Summary

The primary goal of this research is to develop an efficient oil well filter that will control sand production in an oil well. An oil well filter must be capable of allowing heavy oil fluids to flow through its porous structure and restrict the amount of sand that flows through the filter. In addition, the oil well filter must also be durable to the well conditions, that is, remain chemically, physically and mechanically stable over the life span of the filter. In heavy oil wells, the fluid flow is a slurry of heavy oil, produced water and sand. The heavy oil contains compounds and elements such as aliphatic and aromatic hydrocarbons, and sulphur. It is distinguished from conventional oil by its high viscosity. Produced water, also found in heavy oil wells, is characterized by its high salt content with a typical pH ranging from 7 to 12. To bring the oil to the surface, pressure is exerted on the oil and the filter. To consider a filter efficient, it is required to maintain both permeability and durability over its life span. The specific objective of this research was to determine the effects of exposure to oil well fluids on the mechanical and physical properties of selected geotextile filter fabrics.

The permeability of a geotextile filter fabric is determined by its permittivity and transmissivity. Permittivity is the flow of liquid normal to the surface of a fabric, whereas transmissivity is the in-plane flow of liquid through a fabric. The spaces between the fibres in a nonwoven geotextile filter fabric make it an ideal structure for filtration because they allow both types of flow through the fabric. In order for the fabric to maintain its permeability, the physical and mechanical properties of the fibres and fabric must not be affected. In effect, the fibres must not swell in the oil well fluids or the strength be reduced by the pressure exerted on it.

Kerr et al (1988) discussed the criteria that a filter fabric must withstand to be an efficient oil well filter. In addition to maintaining permeability, the fabric must be able to retain a burst strength of 1 to 2MPa, which is an estimate of the down hole sand pressure in an oil well. The polymers in the fibres must not swell in the heavy oil or the produced water. Comparison of the solubility parameters of oil fluids and polymers are used to predict whether a fibre will swell in fluid. If the polymer has similar polar groups and a similar solubility parameter to the fluid it is immersed in, it will probably swell in the fluid. Nonpolar molecules of heavy oil are likely to be attracted to the nonpolar molecules of fibres such as polyester and polypropylene, whereas, these fibres will not attract polar water molecules. McClung (1988) surveyed all the available literature from manufacturers of nonwoven geotextiles to select fabrics for initial permeability and durability testing. Nine nonwoven fabrics made from polyester and polypropylene were tested for permeability and of these fabrics, three were selected for further durability and permeability testing. Two of the fabrics were polyester, Q200 (Wellman Quline) and TTNT (Rhone Poulenc), and the P0820 (Exxon) was polypropylene.

To determine how durable the three fabrics would be if used in an oil well filter they were exposed to well fluids, then selected physical and mechanical properties were measured. Specimens from the three fabrics were immersed in heavy oil and simulated produced water for 0, 30, 60 and 120 days. The burst test which measures the biaxial strength of the fabric was selected to determine the strength of the fabrics. Although the burst test may not predict how a fabric will perform in the oil well application, it generates a two-dimensional tension which is similar to the field conditions (Luong and Bernhard, 1990). To determine if surface changes occurred to the fibres after immersion in the heavy oil, the fibres were observed under the scanning electron microscope. Energy dispersive x-ray analysis (EDXA) was used to determine if oil was present in the fibres. To quantify the interaction of the heavy oil with the fibres, fibre diameter was measured and the amount of swelling, which reflects the interaction of the oil and produced water with the fibres, was determined.

The results of this study indicate that all three fabrics could potentially be used as a filter fabric in a heavy oil well. Scanning electron microscopy (SEM) revealed there was very little change to the surface of the fibres. For all three fibres, the striations on the surface were less visible after immersion in heavy oil for 120 days. Localized fibre swelling was observed on the polypropylene P0820 fibres, although it was not evident on the polyester Q200 or TTNT fibres. The circular cross-sectional shape of the fibres remained unchanged. The characteristics of the three nonwoven fabric structures were readily visible under SEM. The P0820 fibres were randomly laid and variable in diameter, whereas, the fibres in the Q200 and TTNT were more oriented and uniform in fibre diameter. The spaces between the fibres were observed. Typically, the diameter of the fibres was about 25 µm and the spaces between the fibres were about five times greater or 125 µm. EDXA revealed that sulphur, an element of oil, was present in the cross section of the P0820 fibres.

Evidence of fibre swelling was determined by measuring the change in fibre diameter. For all three fibres very little swelling was observed after the fibres had been immersed in the produced water and some swelling was observed after immersion in the heavy oil. Polyester and polypropylene fibres are known as oleophillic, hydrophobic fibres, therefore it was expected there would be some swelling in the heavy oil and very little swelling in the produced water. The greatest amount of swelling that occurred in the produced water was 3% in the polypropylene P0820 fibres. The maximum swelling observed in oil was 18% after the P0820 fibres had been immersed for 120 days. Neither the polyester Q200 nor the TTNT showed an increase in fibre diameter. The swelling that was observed in the fibres is unlikely to affect the filtration properties of the fabric because the spaces between the randomly laid fibres are approximately five times the fibre diameter. It should be noted, however, that results from permeability testing of the three fabrics indicate that the P0820 fabric showed a decrease in flow of oil through the fabric after it had been conditioned in oil for 28 days then tested for permeability. The flow of oil was one third less than when water was filtered through it (Kerr et al, 1990). The reason for the change in permeability is being investigated. Fibre swelling is only one possible explanation.

The resistance of these fabrics to heavy oil and produced water was not only reflected in fibre diameter changes but also in the results from burst testing. All three fabrics maintained a burst strength above 2 MPa after immersion in the heavy oil and produced water. The Q200 had a burst strength 3.17 MPa, the TTNT had a burst strength above 6 MPa and the P0820 had a burst strength of 2.28 MPa. The polyester Q200 and TTNT results suggests that the burst strength will not decrease to 2MPa after immersion in oil and only Q200 will reach that value after immersion in water for three years. The polypropylene P0820 fabric will reach a burst strength of 2MPa after approximately 7 months immersion in heavy oil and produced water. It is doubtful that even at a pressure of 2 MPa the fabric would fail since the filter is a composite structure and other the layers would support the fabric.

It must be recalled that the ultimate purpose of this research is to design an *efficient* oil well filter. The design must incorporate materials that exhibit superior properties and are readily obtainable. Although the cost of designing the heavy oil filter has not been addressed in this study, it will be a consideration in the oil industry. The TTNT geotextile filter fabric is a complex fabric structure manufactured in France. The cost of producing this fabric is higher than the cost of producing the needle-punched Q200 fabric, which is manufactured in the United States. In addition, the cost of transportation of the materials to the area of end use must be considered. Logistically, it would make sense to purchase the geotextile fabric from a company which can take advantage of lower tarrifs and transportation costs.

Conclusions

The criteria for selecting a nonwoven filter fabric are permeability, strength above 2 MPa, durability and cost. Based on these criteria and the findings of this study it can be concluded that polyester fibres may be used in a nonwoven fabric structure for an oil well filter in the Lloydminster area. The polyester fabrics tested exhibited chemical stability in the oil well fluids; no swelling was observed in the fibres. They exhibited a high strength, above 2 MPa after immersion in the oil well fluids, therefore, it can be concluded that these particular fabrics meet the durability and strength criteria for selection of an oil well filter.

Although the durability and permeability criteria are equally important in the well filter design, it is much easier to adjust the opening size of the fabric structure than to change the properties of the fibres. Polyester nonwoven geotextiles may be cheaply manufactured in a wide range of fabric weights. Even if the permeability of these fabrics is determined to be below that required for efficient filtration, the opening size may be adjusted to meet the requirements for an oil well. Manufacturers regularly produce geotextiles to specific opening sizes.

Suggestions for Future Research

1. A long term immersion test should be conducted to determine the combined affect of the heavy oil and produced water on the physical and mechanical properties of polyester geotextiles.

2. A field test should be conducted to determine the combined affect of oil and produced water being filtered simultaneously through the polyester geotextiles on the durability and permeability properties.

3. After long term immersion in oil, the filter fabrics should be examined for changes in density and changes in crystallinity to determine how far the oil penetrated into the fibre structure.

4. To determine changes in extensibility and initial modulus as well as burst strength of the fabrics, a different type of burst tester should be used.

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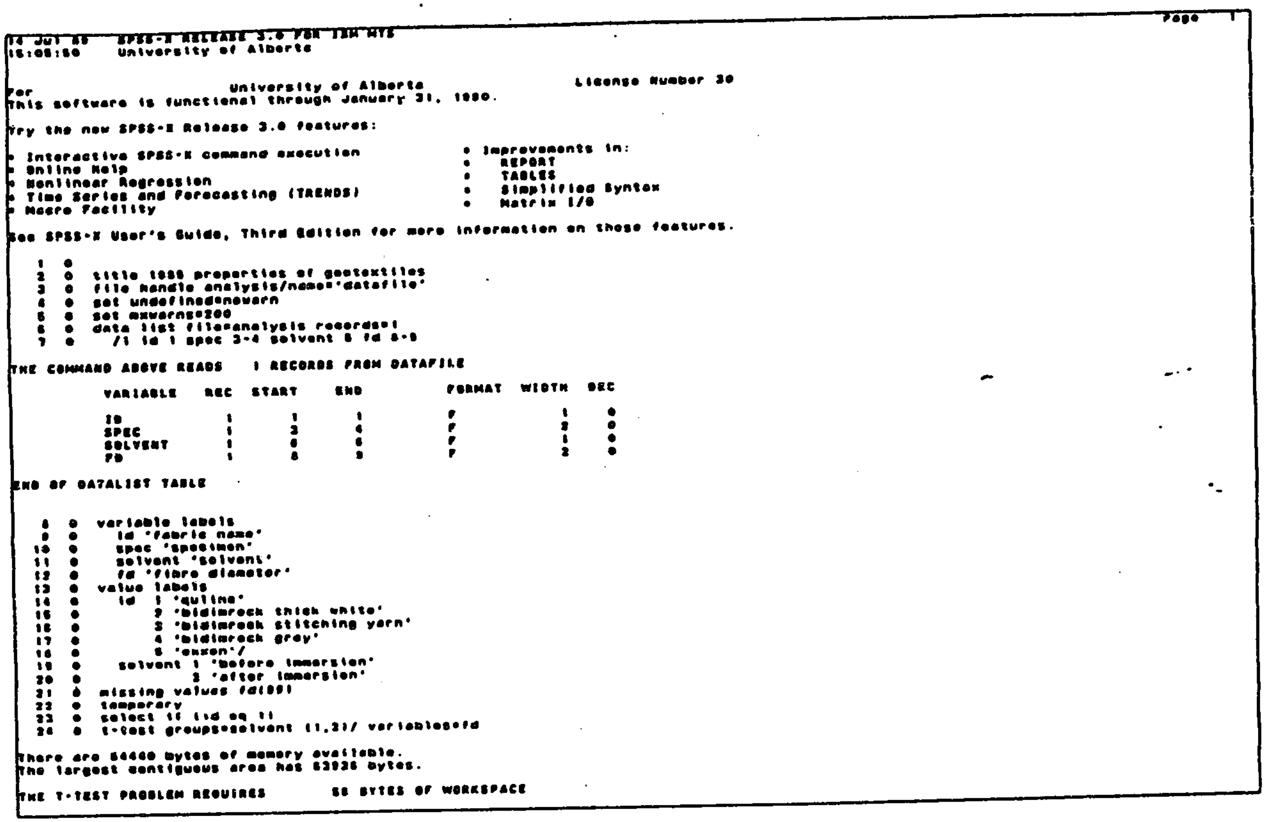
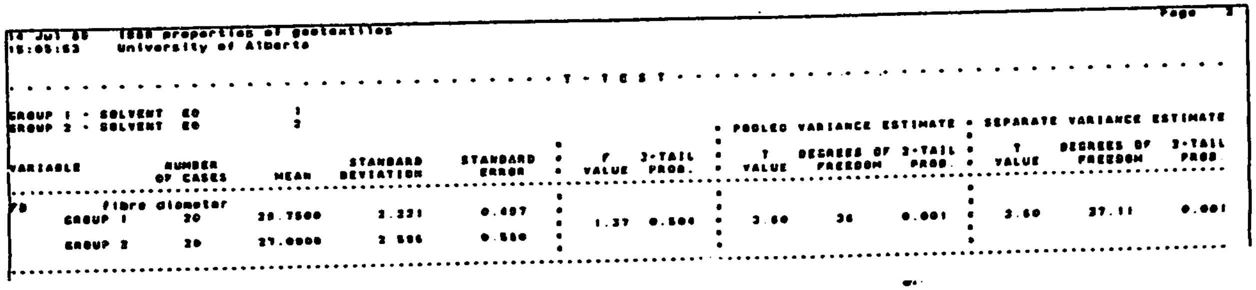
APPENDIX A-1 TWO-TAIL STUDENT T-TEST FOR FIBRE DIAMETER AFTER IMMERSION IN VARSOL SOLVENT



```
14 Jul 89   SPSS-X RELEASE 3.0 FOR IBM MTS                                                  Page   1
15:05:50    University of Alberta

For                      University of Alberta                  License Number 30
This software is functional through January 31, 1990.

Try the new SPSS-X Release 3.0 features:

* Interactive SPSS-X command execution               * Improvements in:
* Online Help                                        *    REPORT
* Nonlinear Regression                               *    TABLES
* Time Series and Forecasting (TRENDS)               *    Simplified Syntax
* Macro Facility                                     *    Matrix I/O

See SPSS-X User's Guide, Third Edition for more information on these features.

   1  0
   2  0  title 1988 properties of geotextiles
   3  0  file handle analysis/name='datafile'
   4  0  set undefined=nowarn
   5  0  set mxwarns=200
   6  0  data list file=analysis records=1
   7  0    /1 id 1 spec 3-4 solvent 6 fd 8-9

THE COMMAND ABOVE READS   1 RECORDS FROM DATAFILE

          VARIABLE   REC  START    END        FORMAT  WIDTH  DEC

          ID           1      1      1        F           1    0
          SPEC         1      3      4        F           2    0
          SOLVENT      1      6      6        F           1    0
          FD           1      8      9        F           2    0

END OF DATALIST TABLE

   8  0  variable labels
   9  0    id 'fabric name'
  10  0    spec 'specimen'
  11  0    solvent 'solvent'
  12  0    fd 'fibre diameter'
  13  0  value labels
  14  0    id  1 'quline'
  15  0        2 'bidimrock thick white'
  16  0        3 'bidimrock stitching yarn'
  17  0        4 'bidimrock grey'
  18  0        5 'exxon'/
  19  0    solvent 1 'before immersion'
  20  0            2 'after immersion'
  21  0  missing values fd(99)
  22  0  temporary
  23  0  select if (id eq 1)
  24  0  t-test groups=solvent (1,2)/ variables=fd

There are 64460 bytes of memory available.
The largest contiguous area has 63936 bytes.

THE T-TEST PROBLEM REQUIRES       56 BYTES OF WORKSPACE
```



```
14 Jul 89   1988 properties of geotextiles                                                                          Page   2
15:05:52    University of Alberta

. . . . . . . . . . . . . . . . . . . . . . . . . . . . T - T E S T . . . . . . . . . . . . . . . . . . . . . . . . . .

GROUP 1 - SOLVENT  EQ        1
GROUP 2 - SOLVENT  EQ        2
                                                                  * POOLED VARIANCE ESTIMATE * SEPARATE VARIANCE ESTIMATE
                                                                  *                          *
                NUMBER               STANDARD   STANDARD  *   F    2-TAIL *   T   DEGREES OF 2-TAIL *   T   DEGREES OF 2-TAIL
VARIABLE       OF CASES     MEAN    DEVIATION    ERROR    * VALUE  PROB.  * VALUE  FREEDOM   PROB.  * VALUE  FREEDOM   PROB.
..........................................................................................................................
FD         fibre diameter                                 *               *                         *
    GROUP 1       20      28.7500      2.221      0.497   *               *                         *
                                                          *  1.37  0.504  *  2.60     38     0.001  *  2.60    37.11   0.001
    GROUP 2       20      27.0000      2.506      0.560   *               *                         *
                                                          *               *                         *
..........................................................................................................................
```

```
                                                                                          Page    3
14 Jul 89    1989 properties of geotextiles
15:05:53     University of Alberta

PRECEDING TASK REQUIRED        0.11 SECONDS CPU TIME;        0.43 SECONDS ELAPSED.

  25  0  temporary
  26  0  select if (id eq 2)
  27  0  t-test groups=solvent (1,2)/ variables=fd

There are 64712 bytes of memory available.
The largest contiguous area has 63920 bytes.

THE T-TEST PROBLEM REQUIRES        56 BYTES OF WORKSPACE
```

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                                                                                          Page    4
14 Jul 89    1989 properties of geotextiles
15:05:53     University of Alberta

- - - - - - - - - - - - - - - - - - - - - - - - - - T - T E S T - - - - - - - - - - - - - - - - - - - - - - - - - -

GROUP 1 - SOLVENT  EQ          1
GROUP 2 - SOLVENT  EQ          2
                                                                 * POOLED VARIANCE ESTIMATE * SEPARATE VARIANCE ESTIMATE
                                                      *                  *                          *
                           NUMBER             STANDARD   STANDARD  *    F     2-TAIL *    T    DEGREES OF 2-TAIL *    T    DEGREES OF  2-TAIL
VARIABLE                  OF CASES    MEAN    DEVIATION    ERROR   *  VALUE   PROB.  *  VALUE   FREEDOM   PROB.  *  VALUE   FREEDOM    PROB.
--------------------------------------------------------------------------------------------------------------------------------
FD         fibre diameter                                          *                 *                           *
    GROUP 1        20        22.0500      1.050      0.235         *  1.99   0.144   *  -2.08     38      0.044  *  -2.08     34.26     0.045
                                                                   *                 *                           *
    GROUP 2        20        22.6500      0.746      0.167         *                 *                           *
--------------------------------------------------------------------------------------------------------------------------------
```

```
                                                                                          Page    5
14 Jul 89    1989 properties of geotextiles
15:05:53     University of Alberta

PRECEDING TASK REQUIRED        0.06 SECONDS CPU TIME;        0.10 SECONDS ELAPSED.

  28  0  temporary
  29  0  select if (id eq 3)
  30  0  t-test groups=solvent (1,2)/ variables=fd

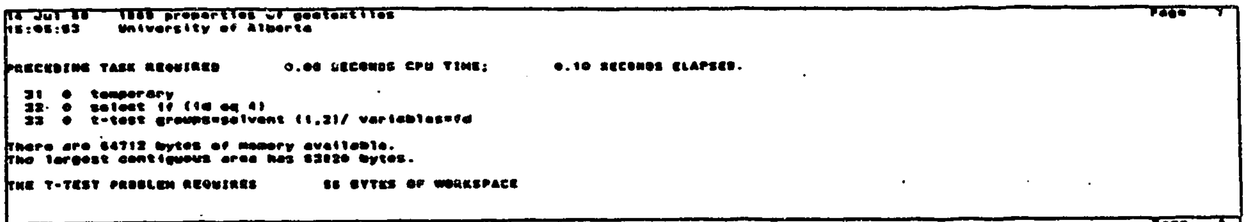
There are 64712 bytes of memory available.
The largest contiguous area has 64208 bytes.

THE T-TEST PROBLEM REQUIRES        56 BYTES OF WORKSPACE
```

```
                                                                                          Page    6
14 Jul 89    1989 properties of geotextiles
15:07:53     University of Alberta

- - - - - - - - - - - - - - - - - - - - - - - - - - T - T E S T - - - - - - - - - - - - - - - - - - - - - - - - - -

GROUP 1 - SOLVENT  EQ          1
GROUP 2 - SOLVENT  EQ          2
                                                                 * POOLED VARIANCE ESTIMATE * SEPARATE VARIANCE ESTIMATE
                                                      *                  *                          *
                           NUMBER             STANDARD   STANDARD  *    F     2-TAIL *    T    DEGREES OF 2-TAIL *    T    DEGREES OF  2-TAIL
VARIABLE                  OF CASES    MEAN    DEVIATION    ERROR   *  VALUE   PROB.  *  VALUE   FREEDOM   PROB.  *  VALUE   FREEDOM    PROB.
--------------------------------------------------------------------------------------------------------------------------------
FD         fibre diameter                                          *                 *                           *
    GROUP 1        20        20.0500      0.999      0.223         *                 *                           *
                                                                   *  1.15   0.763   *   0.46     38      0.650  *   0.46     37.62     0.650
    GROUP 2        20        19.8000      1.071      0.240         *                 *                           *
--------------------------------------------------------------------------------------------------------------------------------
```



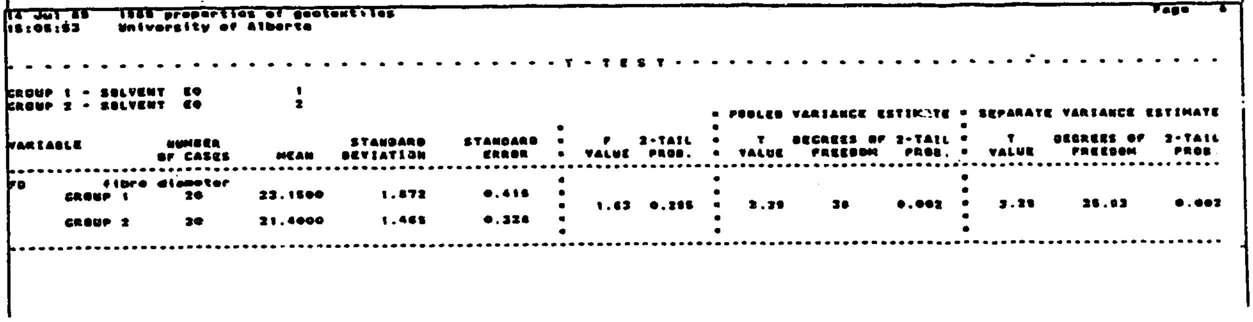
```
14 Jul 88    1988 properties of geotextiles                                                                          Page    7
15:05:53     University of Alberta

PRECEDING TASK REQUIRED       0.06 SECONDS CPU TIME;        0.10 SECONDS ELAPSED.

  31  0  temporary
  32  0  select if (id eq 4)
  33  0  t-test groups=solvent (1,2)/ variables=fd

There are 64712 bytes of memory available.
The largest contiguous area has 63920 bytes.

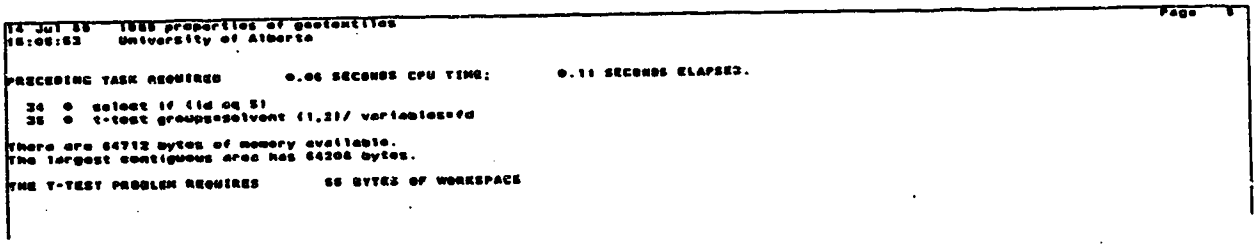
THE T-TEST PROBLEM REQUIRES       56 BYTES OF WORKSPACE
```



```
14 Jul 88    1988 properties of geotextiles                                                                          Page    8
15:05:53     University of Alberta

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - T - T E S T - - - - - - - - - - - - - - - - - - - - - - - - - -

GROUP 1 - SOLVENT  EQ          1
GROUP 2 - SOLVENT  EQ          2
                                                                         * POOLED VARIANCE ESTIMATE * SEPARATE VARIANCE ESTIMATE
                                                              *                    *                           *
VARIABLE          NUMBER                 STANDARD    STANDARD *    F    2-TAIL     *   T    DEGREES OF 2-TAIL  *   T    DEGREES OF  2-TAIL
                 OF CASES       MEAN    DEVIATION      ERROR  *  VALUE   PROB.     * VALUE   FREEDOM   PROB.   * VALUE   FREEDOM    PROB.
----------------------------------------------------------------------------------------------------------------------------------------
FD       fibre diameter                                       *                    *                           *
     GROUP 1        20       23.1500       1.872       0.418  *                    *                           *
                                                              *   1.63  0.295      *  3.29      38     0.002   *  3.29     35.93    0.002
     GROUP 2        20       21.4000       1.465       0.328  *                    *                           *
                                                              *                    *                           *
----------------------------------------------------------------------------------------------------------------------------------------
```



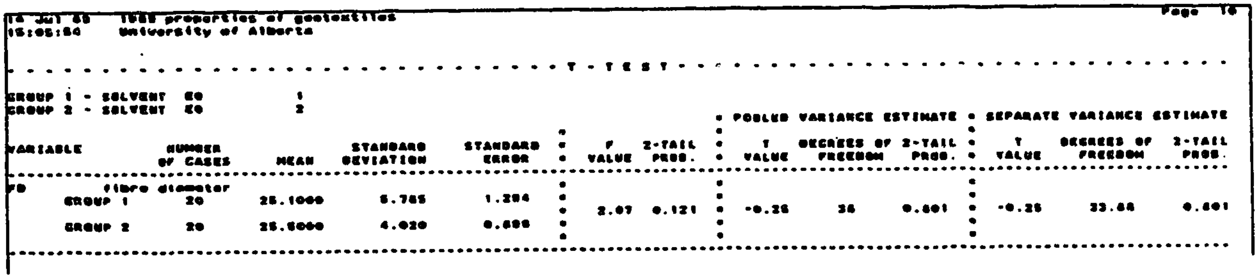
```
14 Jul 88    1988 properties of geotextiles                                                                          Page    9
15:05:53     University of Alberta

PRECEDING TASK REQUIRED       0.06 SECONDS CPU TIME;        0.11 SECONDS ELAPSED.

  34  0  select if (id eq 5)
  35  0  t-test groups=solvent (1,2)/ variables=fd

There are 64712 bytes of memory available.
The largest contiguous area has 64208 bytes.

THE T-TEST PROBLEM REQUIRES       56 BYTES OF WORKSPACE
```



```
14 Jul 88    1988 properties of geotextiles                                                                          Page   10
15:05:54     University of Alberta

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - T - T E S T - - - - - - - - - - - - - - - - - - - - - - - - - -

GROUP 1 - SOLVENT  EQ          1
GROUP 2 - SOLVENT  EQ          2
                                                                         * POOLED VARIANCE ESTIMATE * SEPARATE VARIANCE ESTIMATE
                                                              *                    *                           *
VARIABLE          NUMBER                 STANDARD    STANDARD *    F    2-TAIL     *   T    DEGREES OF 2-TAIL  *   T    DEGREES OF  2-TAIL
                 OF CASES       MEAN    DEVIATION      ERROR  *  VALUE   PROB.     * VALUE   FREEDOM   PROB.   * VALUE   FREEDOM    PROB.
----------------------------------------------------------------------------------------------------------------------------------------
FD       fibre diameter                                       *                    *                           *
     GROUP 1        20       25.1000       5.745       1.284  *                    *                           *
                                                              *   2.07  0.121      * -0.26      38     0.801   * -0.26     33.88    0.801
     GROUP 2        20       25.5000       4.020       0.899  *                    *                           *
                                                              *                    *                           *
----------------------------------------------------------------------------------------------------------------------------------------
```

APPENDIX A-2 MASS AND THICKNESS OF GEOTEXTILES BEFORE IMMERSION IN HEAVY OIL WELL FLUIDS

Mass per Unit Area
(CAN/CGSB 148.1 NO. 2-M85)

Date: May 24, 1989
Fabric: Exxon P0820
State of Specimens: conditioned
Size of Specimens: 20 cm2

Specimen	Mass (g)
1 - 10	6.44
Mass (g/m2)	322

Date: May 24, 1989
Fabric: Q200
State of Specimens: conditioned
Size of Specimens: 20 cm2

Specimen	Mass (g)
1 - 10	11.9
Mass (g/m2)	597

Date: May 24, 1989
Fabric: TTNT 200/50
State of Specimens: conditioned
Size of Specimens: 20 cm2

Specimen	Mass (g)
1 - 10	16.4
Mass (g/m2)	822

THICKNESS OF GEOTEXTILES
(CAN/CGSB 148.1 No.3-M85)

Relative Humidity: 60%
Temperature: 68 F
Date: May 5, 1989
Fabric: Exxon P0820

Machine Used: Frazer
Foot Diameter: 3 inches

SPECIMEN #	THICKNESS
P0820	(Under 2 kPa Pressure)
1	0.116
2	0.114
3	0.121
4	0.119
5	0.123
6	0.119
7	0.122
8	0.12
9	0.119
10	0.121
AVERAGE [illegible]s)	0.119
AVERA[illegible]	3.03
STANDARD DE[illegible]	0.00

Relative Humidity: 60%
Temperature: 68 F
Date:.May 5, 1989
Fabric: Q200

Machine Used: Frazer
Foot Diameter: 3 inches

SPECIMEN #	THICKNESS
P0820	(Under 2 kPa Pressure)
1	0.182
2	0.16
3	0.173
4	0.164
5	0.156
6	0.188
7	0.179
8	0.167
9	0.134
10	0.169
AVERAGE (inches)	0.167
AVERAGE (MM)	4.25
STANDARD DEVIATION	0.02

Relative Humidity: 60%
Temperature: 68 F
Date: May 5, 1989
Fabric: TTNT 200/50

Machine Used: Frazer
Foot Diameter: 3 inches

SPECIMEN #	THICKNESS
P0820	(Under 2 kPa Pressure)
1	0.102
2	0.096
3	0.100
4	0.103
5	0.102
6	0.104
7	0.100
8	0.099
9	0.100
10	0.098
AVERAGE (inches)	0.100
AVERAGE (MM)	2.55
STANDARD DEVIATION	0.00

APPENDIX A-3 BURST TEST DATA FOR GEOTEXTILES AFTER IMMERSION IN HEAVY OIL WELL FLUIDS

CONDITION: 0 DAYS			
SPECIMEN #	PLOTTER VALUE	CONVERSION FACTOR	BURST STRENGTH (MPa)
P0820			
1	2.10	1.413	2.97
2	1.98	1.413	2.80
3	2.03	1.413	2.87
4	2.09	1.413	2.95
5	1.61	1.413	2.27
6	1.75	1.413	2.47
7	1.85	1.413	2.61
8	1.89	1.413	2.67
9	2.00	1.413	2.83
10	2.95	1.413	4.17
		AVERAGE	2.86
		STANDARD DEVIATION	0.51
Q200			
1	2.41	1.413	3.41
2	2.38	1.413	3.36
3	2.50	1.413	3.53
4	2.20	1.413	3.11
5	2.12	1.413	3.00
6	2.34	1.413	3.31
7	2.48	1.413	3.50
8	2.42	1.413	3.42
9	2.32	1.413	3.28
10	2.33	1.413	3.29
		AVERAGE	3.32
		STANDARD DEVIATION	0.17
200/50TTNT			
1	4.10	1.413	5.79
2	4.35	1.413	6.15
3	3.10	1.413	4.38
4	4.51	1.413	6.37
5	5.25	1.413	7.42
6	4.79	1.413	6.77
7	4.81	1.413	6.80
8	4.91	1.413	6.94
9	4.50	1.413	6.36
10	4.45	1.413	6.29
		AVERAGE	6.33
		STANDARD DEVIATION	0.82

CONDITION: 30 DAYS IMMERSION IN DISTILLED WATER			
SPECIMEN #	PLOTTER VALUE	CONVERSION FACTOR	BURST STRENGTH (MPa)
P0820			
1	1.80	1.413	2.54
2	1.41	1.413	1.99
3	2.11	1.413	2.98
4	1.80	1.413	2.54
5	1.55	1.413	2.19
6	2.18	1.413	3.08
7	1.70	1.413	2.40
8	2.10	1.413	2.97
9	2.15	1.413	3.04
10	1.50	1.413	2.12
		AVERAGE	2.59
		STANDARD DEVIATION	0.41
Q200			
1	2.70	1.413	3.82
2	2.58	1.413	3.65
3	2.55	1.413	3.60
4	2.70	1.413	3.82
5	2.68	1.413	3.79
6	2.89	1.413	4.08
7	2.41	1.413	3.41
8	2.50	1.413	3.53
9	2.90	1.413	4.10
10	2.75	1.413	3.89
		AVERAGE	3.77
		STANDARD DEVIATION	0.23
200/50TTNT			
1	4.29	1.413	6.06
2	5.45	1.413	7.70
3	5.30	1.413	7.49
4	5.75	1.413	8.12
5	5.25	1.413	7.42
6	4.70	1.413	6.64
7	5.75	1.413	8.12
8	5.75	1.413	8.12
9	5.72	1.413	8.08
10	5.75	1.413	8.12
		AVERAGE	7.59
		STANDARD DEVIATION	0.72

CONDITION: 30 DAYS IMMERSION IN PRODUCED WATER			
SPECIMEN #	PLOTTER VALUE	CONVERSION FACTOR	BURST STRENGTH
P0820			(MPa)
1	1.90	1.413	2.68
2	2.20	1.413	3.11
3	1.63	1.413	2.30
4	1.80	1.413	2.54
5	1.90	1.413	2.68
6	2.21	1.413	3.12
7	1.48	1.413	2.09
8	1.65	1.413	2.33
9	1.85	1.413	2.61
10	2.35	1.413	3.32
		AVERAGE	2.68
		STANDARD DEVIATION	0.40
Q200			
1	3.35	1.413	4.73
2	3.11	1.413	4.39
3	3.30	1.413	4.66
4	3.10	1.413	4.38
5	2.45	1.413	3.46
6	2.98	1.413	4.21
7	2.94	1.413	4.15
8	2.70	1.413	3.82
9	3.05	1.413	4.31
10	2.75	1.413	3.89
		AVERAGE	4.20
		STANDARD DEVIATION	0.39
200/50TTNT			
1	5.28	1.413	7.46
2	5.68	1.413	8.03
3	5.70	1.413	8.05
4	5.41	1.413	7.64
5	5.55	1.413	7.84
6	5.61	1.413	7.93
7	5.60	1.413	7.91
8	4.40	1.413	6.22
9	5.60	1.413	7.91
10	5.21	1.413	7.36
		AVERAGE	7.64
		STANDARD DEVIATION	0.55

CONDITION: 30 DAYS IMMERSION IN HEAVY OIL			
SPECIMEN #	PLOTTER VALUE	CONVERSION FACTOR	BURST STRENGTH (MPa)
P0820			
1	2.50	1.413	3.53
2	2.35	1.413	3.32
3	2.07	1.413	2.92
4	1.63	1.413	2.30
5	1.91	1.413	2.70
6	1.49	1.413	2.11
7	1.71	1.413	2.42
8	1.62	1.413	2.29
9	1.40	1.413	1.98
10	DISCARD	1.413	#VALUE!
		AVERAGE	2.62
		STANDARD DEVIATION	0.54
Q200			
1	2.25	1.413	3.18
2	1.90	1.413	2.68
3	2.88	1.413	4.07
4	2.30	1.413	3.25
5	2.21	1.413	3.12
6	2.60	1.413	3.67
7	3.14	1.413	4.44
8	2.21	1.413	3.12
9	2.71	1.413	3.83
10	2.50	1.413	3.53
		AVERAGE	3.49
		STANDARD DEVIATION	0.55
200/50TTNT			
1	5.79	1.413	8.18
2	5.20	1.413	7.35
3	5.65	1.413	7.98
4	5.70	1.413	8.05
5	5.45	1.413	7.70
6	4.63	1.413	6.54
7	5.47	1.413	7.73
8	5.79	1.413	8.18
9	5.81	1.413	8.21
10	5.23	1.413	7.39
		AVERAGE	7.73
		STANDARD DEVIATION	0.52

CONDITION: 60 DAYS IMMERSION IN DISTILLED WATER			
SPECIMEN #	PLOTTER VALUE	CONVERSION FACTOR	BURST STRENGTH (MPa)
P0820			
1	1.98	1.413	2.80
2	1.65	1.413	2.33
3	1.35	1.413	1.91
4	1.70	1.413	2.40
5	2.05	1.413	2.90
6	1.72	1.413	2.43
7	1.60	1.413	2.26
8	1.35	1.413	1.91
9	1.70	1.413	2.40
10	[illegible]	1.413	1.99
		AVERAGE	2.33
		STANDARD DEVIATION	0.34
Q200			
1	2.16	1.413	3.05
2	2.33	1.413	3.29
3	2.30	1.413	3.25
4	2.15	1.413	3.04
5	2.55	1.413	3.60
6	2.19	1.413	3.09
7	2.15	1.413	3.04
8	2.19	1.413	3.09
9	2.25	1.413	3.18
10	2.19	1.413	3.09
		AVERAGE	3.17
		STANDARD DEVIATION	0.17
200/50TTNT			
1	5.53	1.413	7.81
2	5.51	1.413	7.79
3	5.45	1.413	7.70
4	4.39	1.413	6.20
5	5.28	1.413	7.46
6	4.74	1.413	6.70
7	4.89	1.413	6.91
8	4.80	1.413	6.78
9	4.48	1.413	6.33
10	5.79	1.413	8.18
		AVERAGE	7.19
		STANDARD DEVIATION	0.69

CONDITION: 60 DAYS IMMERSION IN PRODUCED WATER			
SPECIMEN #	PLOTTER VALUE	CONVERSION FACTOR	BURST STRENGTH (MPa)
P0820			
1	1.70	1.413	2.40
2	1.90	1.413	2.68
3	1.63	1.413	2.30
4	1.70	1.413	2.40
5	1.85	1.413	2.61
6	1.70	1.413	2.40
7	1.30	1.413	1.84
8	1.40	1.413	1.98
9	1.56	1.413	2.20
10	1.60	1.413	2.26
		AVERAGE	2.31
		STANDARD DEVIATION	0.26
Q200			
1	2.25	1.413	3.18
2	1.95	1.413	2.76
3	2.16	1.413	3.05
4	2.16	1.413	3.05
5	2.35	1.413	3.32
6	2.10	1.413	2.97
7	2.00	1.413	2.83
8	2.19	1.413	3.09
9	2.00	1.413	2.83
10	2.10	1.413	2.97
		AVERAGE	3.00
		STANDARD DEVIATION	0.17
200/50TTNT			
1	5.61	1.413	7.93
2	4.71	1.413	6.66
3	5.20	1.413	7.35
4	4.25	1.413	6.01
5	5.05	1.413	7.14
6	4.35	1.413	6.15
7	4.20	1.413	5.93
8	4.03	1.413	5.69
9	4.07	1.413	5.75
10	4.08	1.413	5.77
		AVERAGE	5.44
		STANDARD DEVIATION	0.79

CONDITION: 60 DAYS IMMERSION IN HEAVY OIL			
SPECIMEN #	PLOTTER VALUE	CONVERSION FACTOR	BURST STRENGTH (MPa)
P0820			
1	1.56	1.413	2.20
2	2.19	1.413	3.09
3	1.91	1.413	2.70
4	1.50	1.413	2.12
5	1.40	1.413	1.98
6	2.01	1.413	2.84
7	1.38	1.413	1.95
8	1.95	1.413	2.76
9	1.69	1.413	2.39
10	1.68	1.413	2.37
		AVERAGE	2.44
		STANDARD DEVIATION	0.39
Q200			
1	2.28	1.413	3.22
2	2.30	1.413	3.25
3	2.80	1.413	3.96
4	2.16	1.413	3.05
5	2.10	1.413	2.97
6	2.30	1.413	3.25
7	2.18	1.413	3.08
8	2.31	1.413	3.26
9	2.09	1.413	2.95
10	2.13	1.413	3.01
		AVERAGE	3.20
		STANDARD DEVIATION	0.29
200/50TTNT			
1	5.00	1.413	7.07
2	4.93	1.413	6.97
3	5.00	1.413	7.07
4	5.61	1.413	7.93
5	5.60	1.413	7.91
6	3.71	1.413	5.24
7	5.20	1.413	7.35
8	4.58	1.413	6.47
9	4.57	1.413	6.46
10	5.51	1.413	7.79
		AVERAGE	7.02
		STANDARD DEVIATION	0.82

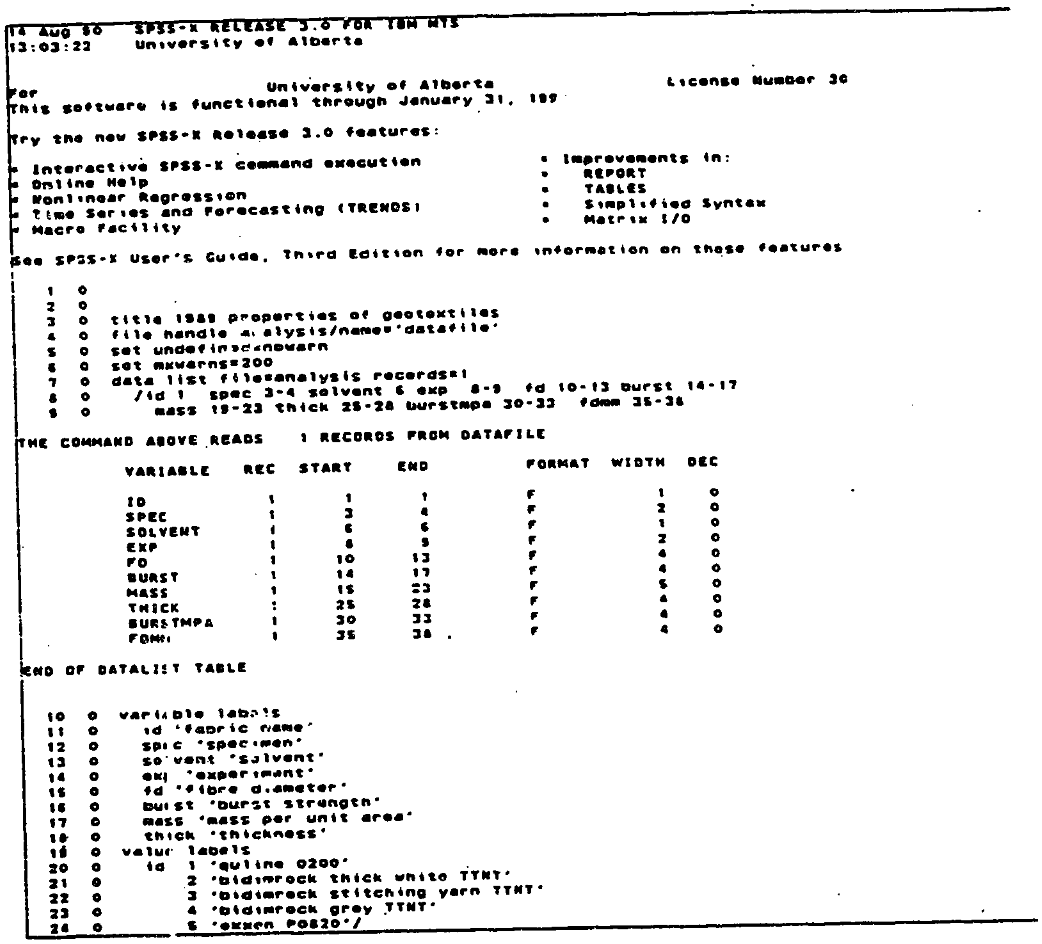
CONDITION: 120 DAYS IMMERSION IN DISTILLED WATER			
SPECIMEN #	PLOTTER VALUE	CONVERSION FACTOR	BURST STRENGTH (MPa)
P0820			
1	2.00	1.413	2.83
2	1.62	1.413	2.29
3	1.90	1.413	2.68
4	1.40	1.413	1.98
5	1.50	1.413	2.12
6	1.60	1.413	2.26
7	1.35	1.413	1.91
8	1.60	1.413	2.26
9	1.35	1.413	1.91
10	1.92	1.413	2.71
		AVERAGE	2.29
		STANDARD DEVIATION	0.34
Q200			
1	2.00	1.413	2.83
2	1.80	1.413	2.54
3	2.11	1.413	2.98
4	1.99	1.413	2.81
5	1.99	1.413	2.81
6	2.05	1.413	2.90
7	1.85	1.413	2.61
8	1.80	1.413	2.54
9	2.05	1.413	2.90
10	1.90	1.413	2.68
		AVERAGE	2.76
		STANDARD DEVIATION	0.16
200/50TTNT			
1	4.60	1.413	6.50
2	4.60	1.413	6.50
3	4.60	1.413	6.50
4	4.60	1.413	6.50
5	4.60	1.413	6.50
6	4.55	1.413	6.43
7	4.59	1.413	6.49
8	4.65	1.413	6.57
9	4.35	1.413	6.15
10	4.65	1.413	6.57
		AVERAGE	6.47
		STANDARD DEVIATION	0.12

CONDITION: 120 DAYS IMMERSION IN PRODUCED WATER

SPECIMEN #	PLOTTER VALUE	CONVERSION FACTOR	BURST STRENGTH (MPa)
P0820			
1	1.89	1.413	2.67
2	1.65	1.413	2.33
3	2.38	1.413	3.36
4	1.61	1.413	2.27
5	1.55	1.413	2.19
6	1.85	1.413	2.61
7	1.75	1.413	2.47
8	1.69	1.413	2.39
9	1.30	1.413	1.84
10	1.50	1.413	2.12
		AVERAGE	2.43
		STANDARD DEVIATION	0.41
Q200			
1	2.31	1.413	3.26
2	2.41	1.413	3.41
3	2.21	1.413	3.12
4	1.98	1.413	2.80
5	2.20	1.413	3.11
6	2.43	1.413	3.43
7	2.00	1.413	2.83
8	1.99	1.413	2.81
9	2.69	1.413	3.80
10	DISCARD	1.413	#VALUE!
		AVERAGE	3.17
		STANDARD DEVIATION	0.34
200/50TTNT			
1	4.50	1.413	6.36
2	4.39	1.413	6.20
3	3.75	1.413	5.30
4	4.11	1.413	5.81
5	4.65	1.413	6.57
6	4.68	1.413	6.61
7	4.65	1.413	6.57
8	4.71	1.413	6.66
9	4.72	1.413	6.67
10	4.70	1.413	6.64
		AVERAGE	6.34
		STANDARD DEVIATION	0.46

CONDITION: 120 DAYS IMMERSION IN HEAVY OIL			
SPECIMEN #	PLOTTER VALUE	CONVERSION FACTOR	BURST STRENGTH (MPa)
P0820			
1	1.55	1.413	2.19
2	1.50	1.413	2.12
3	1.51	1.413	2.13
4	1.81	1.413	2.56
5	1.55	1.413	2.19
6	1.79	1.413	2.53
7	1.90	1.413	2.68
8	1.90	1.413	2.68
9	1.25	1.413	1.77
10	DISCARD	1.413	#VALUE!
		AVERAGE	2.32
		STANDARD DEVIATION	0.31
Q200			
1	2.31	1.413	3.26
2	1.89	1.413	2.67
3	2.68	1.413	3.79
4	2.20	1.413	3.11
5	2.65	1.413	3.74
6	2.50	1.413	3.53
7	2.40	1.413	3.39
8	2.25	1.413	3.18
9	2.30	1.413	3.25
10	DISCARD	1.413	#VALUE!
		AVERAGE	3.33
		STANDARD DEVIATION	0.34
200/50TTNT			
1	4.40	1.413	6.22
2	4.65	1.413	6.57
3	5.25	1.413	7.42
4	5.05	1.413	7.14
5	4.38	1.413	6.19
6	5.70	1.413	8.05
7	4.95	1.413	6.99
8	5.55	1.413	7.84
9	5.28	1.413	7.46
10	4.80	1.413	6.78
		AVERAGE	7.07
		STANDARD DEVIATION	0.64

APPENDIX A-4 STATISTICAL ANALYSIS OF FIBRE DIAMETER MEASUREMENTS AFTER IMMERSION IN HEAVY OIL WELL FLUIDS



```
14 Aug 90     SPSS-X RELEASE 3.0 FOR IBM MTS
13:03:22      University of Alberta

                          University of Alberta                    License Number 30
For
This software is functional through January 31, 199

Try the new SPSS-X Release 3.0 features:

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* Macro Facility                                         *    Matrix I/O

See SPSS-X User's Guide, Third Edition for more information on these features

    1  0
    2  0
    3  0  title 1989 properties of geotextiles
    4  0  file handle analysis/name='datafile'
    5  0  set undefined=nowarn
    6  0  set mxwarns=200
    7  0  data list file=analysis records=1
    8  0    /id 1  spec 3-4 solvent 6 exp  8-9  fd 10-13 burst 14-17
    9  0      mass 19-23 thick 25-28 burstmpa 30-33  fdmm 35-38

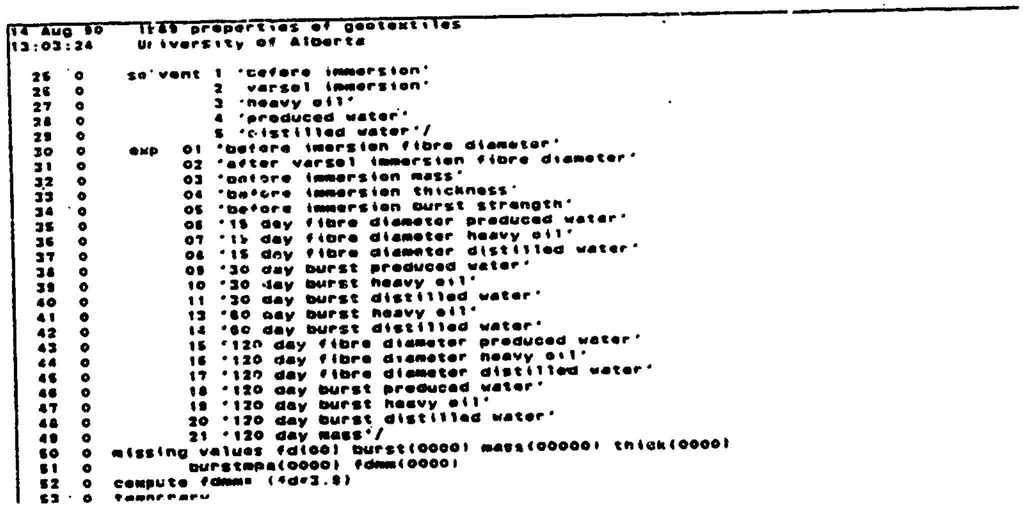
THE COMMAND ABOVE READS    1 RECORDS FROM DATAFILE

           VARIABLE   REC  START     END          FORMAT  WIDTH  DEC

           ID           1      1       1          F           1    0
           SPEC         1      3       4          F           2    0
           SOLVENT      1      6       6          F           1    0
           EXP          1      8       9          F           2    0
           FD           1     10      13          F           4    0
           BURST        1     14      17          F           4    0
           MASS         1     19      23          F           5    0
           THICK        1     25      28          F           4    0
           BURSTMPA     1     30      33          F           4    0
           FDMM         1     35      38 .        F           4    0

END OF DATALIST TABLE

   10  0  variable labels
   11  0    id 'fabric name'
   12  0    spec 'specimen'
   13  0    solvent 'solvent'
   14  0    exp 'experiment'
   15  0    fd 'fibre diameter'
   16  0    burst 'burst strength'
   17  0    mass 'mass per unit area'
   18  0    thick 'thickness'
   19  0  value labels
   20  0    id  1 'quline 0200'
   21  0          2 'bidimrock thick white TTNT'
   22  0          3 'bidimrock stitching yarn TTNT'
   23  0          4 'bidimrock grey TTNT'
   24  0          5 'exxon P0820'/
```



```
14 Aug 90     1989 properties of geotextiles
13:03:24      University of Alberta

  25  0     solvent 1 'before immersion'
  26  0             2  varsol immersion'
  27  0             3 'heavy oil'
  28  0             4 'produced water'
  29  0             5 'distilled water'/
  30  0      exp   01 'before imersion fibre diameter'
  31  0            02 'after varsol immersion fibre diameter'
  32  0            03 'before immersion mass'
  33  0            04 'before immersion thickness'
  34  0            05 'before immersion burst strength'
  35  0            06 '15 day fibre diameter produced water'
  36  0            07 '15 day fibre diameter heavy oil'
  37  0            08 '15 day fibre diameter distilled water'
  38  0            09 '30 day burst produced water'
  39  0            10 '30 day burst heavy oil'
  40  0            11 '30 day burst distilled water'
  41  0            13 '60 day burst heavy oil'
  42  0            14 '60 day burst distilled water'
  43  0            15 '120 day fibre diameter produced water'
  44  0            16 '120 day fibre diameter heavy oil'
  45  0            17 '120 day fibre diameter distilled water'
  46  0            18 '120 day burst produced water'
  47  0            19 '120 day burst heavy oil'
  48  0            20 '120 day burst distilled water'
  49  0            21 '120 day mass'/
  50  0  missing values fd(00) burst(0000) mass(00000) thick(0000)
  51  0            burstmpa(0000) fdmm(0000)
  52  0  compute fdmm= (fd/3.8)
  53  0  temporary
```

```
14 Aug 90    1585 properties of geotextiles
13:03:26     University of Alberta

- - - - - - - - - - - - - - - - - - - - - - - - - - - O N E W A Y - - - - - - - - - - - - - - - -

       Variable  FDMM
    By Variable  EXP           experiment
                                     ANALYSIS OF VARIANCE

                                  SUM OF          MEAN              F        F
        SOURCE           D.F.    SQUARES        SQUARES           RATIO    PROB.

BETWEEN GROUPS             2     35.2953        17.6477          2.2035    .1141

WITHIN GROUPS            147   1177.3361         8.0091

TOTAL                    149   1212.6314


                                  STANDARD   STANDARD
GROUP        COUNT        MEAN   DEVIATION     ERROR     MINIMUM     MAXIMUM     95 PCT CONF INT FOR MEAN

Grp 1           50     29.7256     2.1043      .2976     24.8800     34.7100     29.1278 TO    30.3234
Grp 2           50     28.5556     3.4111      .4824     23.0100     35.8800     27.5854 TO    29.5252
Grp 3           50     29.3202     2.8219      .3991     23.4000     39.3900     28.5182 TO    30.1222

TOTAL          150     29.2005     2.8526      .2329     23.0100     39.3900     28.7403 TO    29.6609

        FIXED EFFECTS MODEL        2.8300      .2311                             28.7439  TO    29.6573

       RANDOM EFFECTS MODEL                    .3430                             27.7248  TO    30.6764

RANDOM EFFECTS MODEL - ESTIMATE OF BETWEEN COMPONENT VARIANCE          0.1928


Tests for Homogeneity of Variances

     Cochrans C = Max. Variance/Sum(Variances) =    .4843, P =  .013 (Approx.)
     Bartlett-Box F =                              5.459 , P =  .004
     Maximum Variance / Minimum Variance            2.628
```

Q200/distilled water/ fibre diameter

```
14 Aug 90    1585 properties of geotextiles
13:03:26     University of Alberta

- - - - - - - - - - - - - - - - - - - - - - - - - - - O N E W A Y - - - - - - - - - - - - - - - -

       Variable  FDMM
    By Variable  EXP           experiment

MULTIPLE RANGE TEST

SCHEFFE PROCEDURE
RANGES FOR THE 0.100 LEVEL -

          3.06   3.06

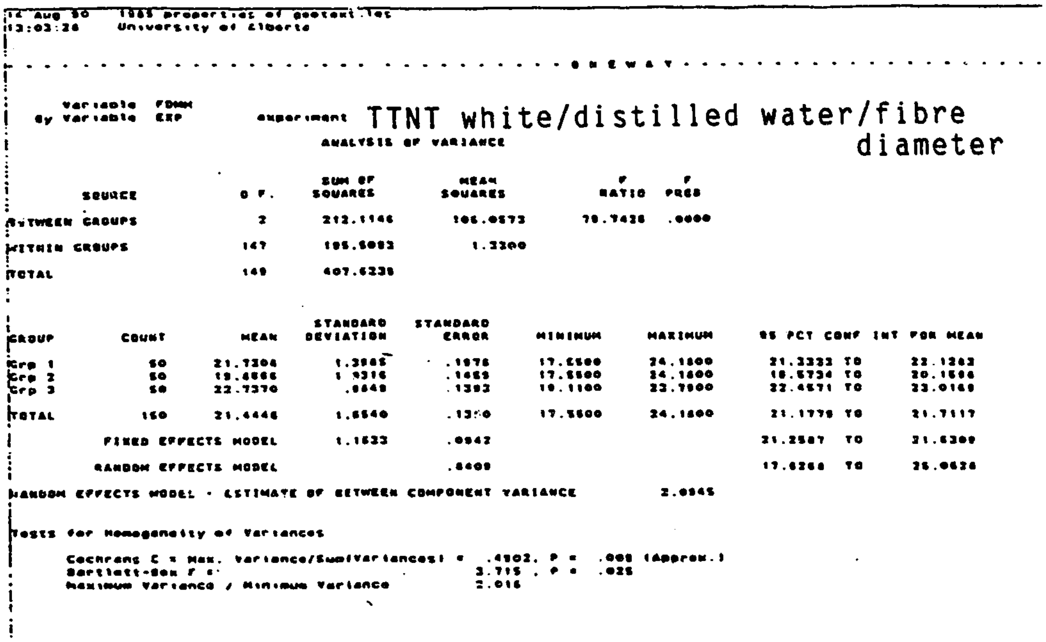
THE RANGES ABOVE ARE TABLE RANGES.
THE VALUE ACTUALLY COMPARED WITH MEAN(J)-MEAN(I) IS..
       2.0011 * RANGE * DSQRT(1/N(I) + 1/N(J))

 NO TWO GROUPS ARE SIGNIFICANTLY DIFFERENT AT THE 0.100 LEVEL

  HOMOGENEOUS SUBSETS    (SUBSETS OF GROUPS, WHOSE HIGHEST AND LOWEST MEANS
                          DO NOT DIFFER BY MORE THAN THE SHORTEST
                          SIGNIFICANT RANGE FOR A SUBSET OF THAT SIZE)

SUBSET   1

GROUP        Grp 2         Grp 3         Grp 1
MEAN        28.5556       29.3202       29.7256
- - - - - - - - - - - - - - - - - - - - - - - -
```



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14 Aug 90    1989 properties of geotextiles
13:03:28     University of Alberta

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     Variable  FDMM
  By Variable  EXP         experiment TTNT white/distilled water/fibre
                                                                   diameter
                               ANALYSIS OF VARIANCE

                                  SUM OF         MEAN             F       F
      SOURCE             D.F.     SQUARES        SQUARES          RATIO   PROB.

BETWEEN GROUPS             2      212.1146       106.0573       79.7428   .0000

WITHIN GROUPS            147      195.5092         1.3300

TOTAL                    149      407.6238


                                     STANDARD   STANDARD
GROUP        COUNT           MEAN   DEVIATION     ERROR      MINIMUM     MAXIMUM      95 PCT CONF INT FOR MEAN

Grp 1           50        21.7304      1.3985      .1978     17.6500     24.1600      21.3333 TO     22.1283
Grp 2           50        19.8666      1.0316      .1459     17.5500     24.1600      19.5734 TO     20.1598
Grp 3           50        22.7370       .9849      .1393     19.1100     23.7900      22.4571 TO     23.0169

TOTAL          150        21.4446      1.6540      .1350     17.5500     24.1600      21.1778 TO     21.7115

         FIXED EFFECTS MODEL           1.1533      .0942                              21.2587  TO    21.6309

        RANDOM EFFECTS MODEL                       .8409                              17.8264  TO    25.0628

RANDOM EFFECTS MODEL - ESTIMATE OF BETWEEN COMPONENT VARIANCE          2.0945


Tests for Homogeneity of Variances

     Cochrans C = Max. Variance/Sum(Variances) =   .4902, P =  .005 (Approx.)
     Bartlett-Box F =                             3.715 , P =  .025
     Maximum Variance / Minimum Variance          2.016
```

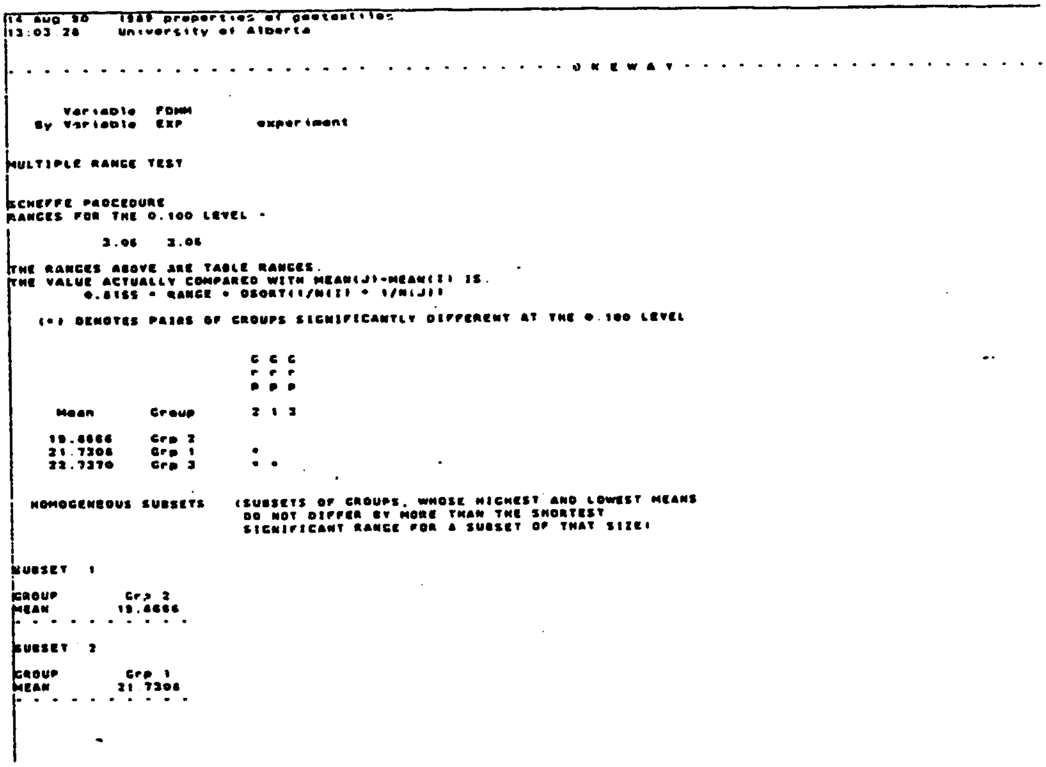

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14 Aug 90    1989 properties of geotextiles
13:03:28     University of Alberta

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     Variable  FDMM
  By Variable  EXP         experiment


MULTIPLE RANGE TEST


SCHEFFE PROCEDURE
RANGES FOR THE 0.100 LEVEL -

           3.06   3.06

THE RANGES ABOVE ARE TABLE RANGES.
THE VALUE ACTUALLY COMPARED WITH MEAN(J)-MEAN(I) IS..
       0.8155 * RANGE * DSQRT(1/N(I) + 1/N(J))

  (*) DENOTES PAIRS OF GROUPS SIGNIFICANTLY DIFFERENT AT THE 0.100 LEVEL


                             G G G
                             r r r
                             p p p

     Mean       Group        2 1 3

    19.8666     Grp 2
    21.7304     Grp 1        *
    22.7370     Grp 3        * *


  HOMOGENEOUS SUBSETS     (SUBSETS OF GROUPS, WHOSE HIGHEST AND LOWEST MEANS
                           DO NOT DIFFER BY MORE THAN THE SHORTEST
                           SIGNIFICANT RANGE FOR A SUBSET OF THAT SIZE)


SUBSET  1

GROUP         Grp 2
MEAN         19.8666
- - - - - - - - - - -

SUBSET  2

GROUP         Grp 1
MEAN         21.7304
- - - - - - - - - - -
```

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14 Aug 90    1989 properties of geotextiles
13 03 30     University of Alberta

- - - - - - - - - - - - - - - - - - - - - - - - - O N E W A Y - - - - - - - - - - - - - - - - - - - - - - - -


        Variable  FDMM
     By Variable  EXP            experiment   TTNT grey/distilled water/fibre diameter
                                          ANALYSIS OF VARIANCE

                                        SUM OF          MEAN              F        F
         SOURCE               D.F.      SQUARES         SQUARES           RATIO    PROB.

BETWEEN GROUPS                  2         18.6900         9.3450          1.8967   .1537

WITHIN GROUPS                 147        724.2515         4.9269

TOTAL                         149        742.9415


                                        STANDARD     STANDARD
GROUP        COUNT         MEAN         DEVIATION       ERROR      MINIMUM      MAXIMUM       95 PCT CONF INT FOR MEAN

Grp 1           50       24.0396         2.4308         .3438     18.1100      29.2500       23.3486 TO       24.7304
Grp 2           50       23.2908         1.9902         .2815     18.5000      27.6900       22.7252 TO       23.8564
Grp 3           50       23.2908         2.2161         .3134     18.1100      31.2000       22.6610 TO       23.9206

TOTAL          150       23.5404         2.2330         .1823     18.1100      31.2000       23.1801 TO       23.9007

           FIXED EFFECTS MODEL           2.2197         .1812                                23.1822  TO      23.8986

          RANDOM EFFECTS MODEL                          .2496                                22.4664  TO      24.6144

RANDOM EFFECTS MODEL - ESTIMATE OF BETWEEN COMPONENT VARIANCE             0.0884

Tests for Homogeneity of Variances

     Cochrans C = Max. Variance/Sum(Variances) =   .3998, P =  .346 (Approx.)
     Bartlett-Box F =                               .965 , P =  .381
     Maximum Variance / Minimum Variance           1.492
```

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14 Aug 90    1989 properties of geotextiles
13:03.30     University of Alberta

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        Variable  FDMM
     By Variable  EXP            experiment

MULTIPLE RANGE TEST

SCHEFFE PROCEDURE
RANGES FOR THE 0.100 LEVEL -

          3.06    3.06

THE RANGES ABOVE ARE TABLE RANGES.
THE VALUE ACTUALLY COMPARED WITH MEAN(J)-MEAN(I) IS..
        1.5695 * RANGE * DSQRT(1/N(I) + 1/N(J))

 NO TWO GROUPS ARE SIGNIFICANTLY DIFFERENT AT THE 0.100 LEVEL

  HOMOGENEOUS SUBSETS    (SUBSETS OF GROUPS, WHOSE HIGHEST AND LOWEST MEANS
                          DO NOT DIFFER BY MORE THAN THE SHORTEST
                          SIGNIFICANT RANGE FOR A SUBSET OF THAT SIZE)


SUBSET  1

GROUP        Grp 2          Grp 3          Grp 1
MEAN        23.2908        23.2908        24.0396
- - - - - - - - - - - - - - - - - - - - - - - - -

        Variable  FDMM
     By Variable  EXP            experiment
                                          ANALYSIS OF VARIANCE P0820/distilled water/fibre
                                                                                    diameter
                                        SUM OF          MEAN              F        F
         SOURCE               D.F       SQUARES         SQUARES           RATIO    PROB

BETWEEN GROUPS                  2         45.3948        22.6974          .7145    .4911

WITHIN GROUPS                 147       4669.6860        31.7666

TOTAL                         149       4715.0807


                                        STANDARD     STANDARD
GROUP        COUNT         MEAN         DEVIATION       ERROR      MINIMUM      MAXIMUM       95 PCT CONF INT FOR MEAN

Grp 1           50       24.9990         5.8222         .8234     17.9400      53.4300       23.3443 TO       26.6537
Grp 2           50       26.3406         5.0804         .7185     19.8900      51.0900       24.8966 TO       27.7846
Grp 3           50       25.7790         5.9655         .8436     18.7200      51.0900       24.0836 TO       27.4744

TOTAL          150       25.7062         5.6254         .4593     17.9400      53.4300       24.7986 TO       26.6138

           FIXED EFFECTS MODEL           5.6362         .4602                                24.7968  TO      26.6156

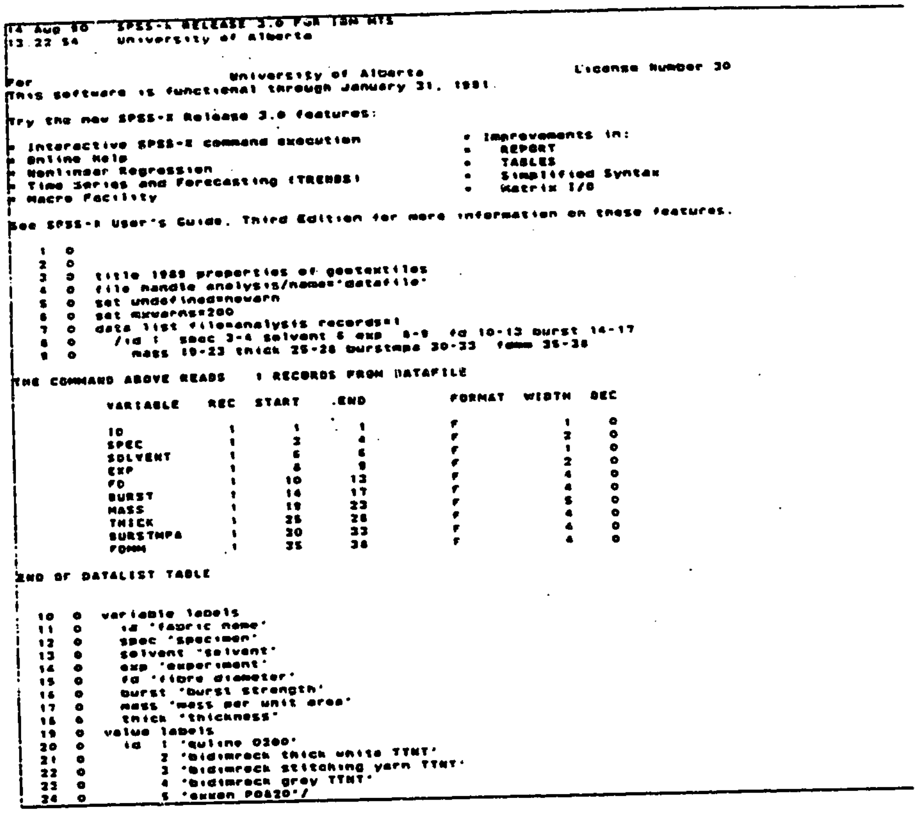
          RANDOM EFFECTS MODEL                          .4602                                23.7261  TO      27.6863

WARNING - BETWEEN COMPONENT VARIANCE IS NEGATIVE
          IT WAS REPLACED BY 0.0 IN COMPUTING ABOVE RANDOM EFFECTS MEASURES

RANDOM EFFECTS MODEL - ESTIMATE OF BETWEEN COMPONENT VARIANCE            -0.1814

Tests for Homogeneity of Variances

     Cochrans C = Max. Variance/Sum(Variances) =   .3734, P =  .688 (Approx.)
     Bartlett-Box F =                               .703 , P =  .495
     Maximum Variance / Minimum Variance           1.379
```



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14 Aug 90   SPSS-X RELEASE 3.0 FOR IBM MTS
13:22:54    University of Alberta

                            University of Alberta                 License Number 30
For
This software is functional through January 31, 1991.

Try the new SPSS-X Release 3.0 features:

* Interactive SPSS-X command execution              * Improvements in:
* Online Help                                        *    REPORT
* Nonlinear Regression                               *    TABLES
* Time Series and Forecasting (TRENDS)               *    Simplified Syntax
* Macro Facility                                     *    Matrix I/O

See SPSS-X User's Guide, Third Edition for more information on these features.

    1  0
    2  0
    3  0   title 1989 properties of geotextiles
    4  0   file handle analysis/name='datafile'
    5  0   set undefined=nowarn
    6  0   set mxwarns=200
    7  0   data list file=analysis records=1
    8  0     /id 1  spec 3-4 solvent 6 exp  8-9  fd 10-13 burst 14-17
    9  0       mass 19-23 thick 25-28 burstmpa 30-33  fdmm 35-38

THE COMMAND ABOVE READS   1 RECORDS FROM DATAFILE

          VARIABLE   REC  START   .END        FORMAT  WIDTH  DEC

          ID           1      1      1        F          1    0
          SPEC         1      3      4        F          2    0
          SOLVENT      1      6      6        F          1    0
          EXP          1      8      9        F          2    0
          FD           1     10     13        F          4    0
          BURST        1     14     17        F          4    0
          MASS         1     19     23        F          5    0
          THICK        1     25     28        F          4    0
          BURSTMPA     1     30     33        F          4    0
          FDMM         1     35     38        F          4    0

END OF DATALIST TABLE


   10  0  variable labels
   11  0     id 'fabric name'
   12  0     spec 'specimen'
   13  0     solvent 'solvent'
   14  0     exp 'experiment'
   15  0     fd 'fibre diameter'
   16  0     burst 'burst strength'
   17  0     mass 'mass per unit area'
   18  0     thick 'thickness'
   19  0   value labels
   20  0     id  1 'quline Q200'
   21  0         2 'bidimrock thick white TTNT'
   22  0         3 'bidimrock stitching yarn TTNT'
   23  0         4 'bidimrock grey TTNT'
   24  0         5 'exxon PO820'/
```

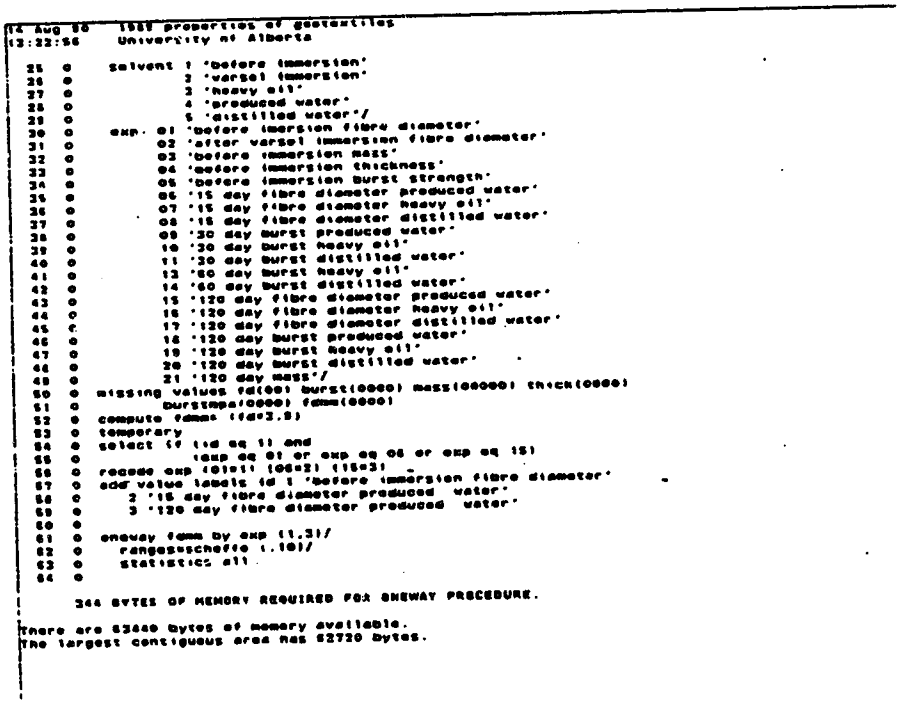

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14 Aug 90    1989 properties of geotextiles
13:22:56     University of Alberta

   25  0      solvent 1 'before immersion'
   26  0              2 'varsol immersion'
   27  0              3 'heavy oil'
   28  0              4 'produced water'
   29  0              5 'distilled water'/
   30  0      exp  01 'before imersion fibre diameter'
   31  0           02 'after varsol immersion fibre diameter'
   32  0           03 'before immersion mass'
   33  0           04 'before immersion thickness'
   34  0           05 'before immersion burst strength'
   35  0           06 '15 day fibre diameter produced water'
   36  0           07 '15 day fibre diameter heavy oil'
   37  0           08 '15 day fibre diameter distilled water'
   38  0           09 '30 day burst produced water'
   39  0           10 '30 day burst heavy oil'
   40  0           11 '30 day burst distilled water'
   41  0           13 '60 day burst heavy oil'
   42  0           14 '60 day burst distilled water'
   43  0           15 '120 day fibre diameter produced water'
   44  0           16 '120 day fibre diameter heavy oil'
   45  0           17 '120 day fibre diameter distilled water'
   46  0           18 '120 day burst produced water'
   47  0           19 '120 day burst heavy oil'
   48  0           20 '120 day burst distilled water'
   49  0           21 '120 day mass'/
   50  0   missing values fd(00) burst(0000) mass(00000) thick(0000)
   51  0           burstmpa(0000) fdmm(0000)
   52  0   compute fdmm= (fd*3.9)
   53  0   temporary
   54  0   select if (id eq 1) and
   55  0           (exp eq 01 or exp eq 06 or exp eq 15)
   56  0   recode exp (01=1) (06=2) (15=3)
   57  0   add value labels id 1 'before immersion fibre diameter'
   58  0      2 '15 day fibre diameter produced  water'
   59  0      3 '120 day fibre diameter produced  water'
   60  0
   61  0   oneway fdmm by exp (1,3)/
   62  0     ranges=scheffe (.10)/
   63  0     statistics all
   64  0

       344 BYTES OF MEMORY REQUIRED FOR ONEWAY PROCEDURE.

There are 53440 bytes of memory available.
The largest contiguous area has 52720 bytes.
```

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14 Aug 90    1988 properties of geotextiles                                                              Page    3
13:22:58     University of Alberta

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       Variable  FDMM
    By Variable  EXP            experiment    Q200/pr. water/ fibre diameter
                                        ANALYSIS OF VARIANCE

                                    SUM OF          MEAN                 F      F
        SOURCE              D.F.    SQUARES         SQUARES              RATIO  PROB.

BETWEEN GROUPS                2       94.6731        47.3366             6.6242  .0018

WITHIN GROUPS               147     1050.4655         7.1460

TOTAL                       149     1145.1386


                                         STANDARD   STANDARD
GROUP          COUNT          MEAN       DEVIATION      ERROR       MINIMUM       MAXIMUM       95 PCT CONF INT FOR MEAN

Grp 1             50       29.7258          2.1043      .2976       24.9600       34.7100       29.1278 TO       30.3238
Grp 2             50       30.4044          2.7723      .3921       23.4000       37.0500       29.6165 TO       31.1923
Grp 3             50       28.4856          3.0536      .4318       21.4500       40.9500       27.6178 TO       29.3534

TOTAL            150       29.5386          2.7723      .2264       21.4500       40.9500       29.0913 TO       29.9859

        FIXED EFFECTS MODEL                 2.6732      .2183                                   29.1073  TO      29.9699

       RANDOM EFFECTS MODEL                             .5618                                   27.1216  TO      31.9557

RANDOM EFFECTS MODEL - ESTIMATE OF BETWEEN COMPONENT VARIANCE              0.8038

Tests for Homogeneity of Variances

       Cochrans C = Max. Variance/Sum(Variances) =   .4349, P =  .108 (Approx.)
       Bartlett-Box F =                              3.392 , P =  .034
       Maximum Variance / Minimum Variance           2.106
```

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14 Aug 90    1988 properties of geotextiles                                                              Page    4
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       Variable  FDMM
    By Variable  EXP            experiment

MULTIPLE RANGE TEST

SCHEFFE PROCEDURE
RANGES FOR THE 0.100 LEVEL -

          3.06   3.06

THE RANGES ABOVE ARE TABLE RANGES.
THE VALUE ACTUALLY COMPARED WITH MEAN(J)-MEAN(I) IS..
         1.8902 * RANGE * DSQRT(1/N(I) + 1/N(J))

   (*) DENOTES PAIRS OF GROUPS SIGNIFICANTLY DIFFERENT AT THE 0.100 LEVEL

                            G G G
                            r r r
                            p p p

     Mean       Group       3 1 2

    28.4856     Grp 3
    29.7258     Grp 1       *
    30.4044     Grp 2       *

  HOMOGENEOUS SUBSETS   (SUBSETS OF GROUPS, WHOSE HIGHEST AND LOWEST MEANS
                         DO NOT DIFFER BY MORE THAN THE SHORTEST
                         SIGNIFICANT RANGE FOR A SUBSET OF THAT SIZE)

SUBSET  1

GROUP        Grp 3
MEAN       28.4856
- - - - - - - - - -

SUBSET  2

GROUP        Grp 1        Grp 2
MEAN       29.7258      30.4044
- - - - - - - - - - - - - - - - -
```

TTNT white/pr. water/fibre diameter

```
      Variable  FDMM
   By Variable  EXP           experiment
                                  ANALYSIS OF VARIANCE

                                      SUM OF         MEAN             F       F
        SOURCE               D.F.    SQUARES       SQUARES          RATIO   PROB.

BETWEEN GROUPS                 2      67.4290       33.7145        13.0110  .0000

WITHIN GROUPS                147     380.9101        2.5912

TOTAL                        149     448.3391


                                     STANDARD     STANDARD
GROUP        COUNT         MEAN     DEVIATION      ERROR       MINIMUM      MAXIMUM       95 PCT CONF INT FOR MEAN

Grp 1          50       21.7306      1.3965        .1975      17.8500      24.1000       21.3323 TO      22.1283
Grp 2          50       20.1706      1.8210        .2700      15.3800      25.2500       19.6282 TO      20.7132
Grp 3          50       20.5062      1.4743        .2085      16.7200      27.3000       20.0872 TO      20.9252

TOTAL         150       20.8025      1.7346        .1416      15.3800      28.2500       20.5227 TO      21.0825

       FIXED EFFECTS MODEL           1.6097        .1314                                 20.5428  TO     21.0823

      RANDOM EFFECTS MODEL                         .4761                                 18.7627  TO     22.8428

RANDOM EFFECTS MODEL - ESTIMATE OF BETWEEN COMPONENT VARIANCE          0.6225

Tests for Homogeneity of Variances

     Cochrans C = Max. Variance/Sum(Variances) =   .4608, P =  .025 (Approx.)
     Bartlett-Box F =                             2.819 , P =  .060
     Maximum Variance / Minimum Variance          1.863




      Variable  FDMM
   By Variable  EXP           experiment

MULTIPLE RANGE TEST

SCHEFFE PROCEDURE
RANGES FOR THE 0.100 LEVEL -

        3.06   3.06

THE RANGES ABOVE ARE TABLE RANGES.
THE VALUE ACTUALLY COMPARED WITH MEAN(J)-MEAN(I) IS..
        1.1382 * RANGE * DSQRT(1/N(I) + 1/N(J))

   (*) DENOTES PAIRS OF GROUPS SIGNIFICANTLY DIFFERENT AT THE 0.100 LEVEL

                         G G G
                         r r r
                         p p p

   Mean       Group      2 3 1

   20.1706    Grp 2
   20.5062    Grp 3
   21.7306    Grp 1      * *

 HOMOGENEOUS SUBSETS    (SUBSETS OF GROUPS, WHOSE HIGHEST AND LOWEST MEANS
                         DO NOT DIFFER BY MORE THAN THE SHORTEST
                         SIGNIFICANT RANGE FOR A SUBSET OF THAT SIZE)

SUBSET  1

GROUP        Grp 2        Grp 3
MEAN       20.1706      20.5062
- - - - - - - - - - - - - - - - -

SUBSET  2

GROUP       Grp 1
MEAN       21.7306
- - - - - - - - - -


      Variable  FDMM
   By Variable  EXP           experiment
                                  ANALYSIS OF VARIANCE

                                      SUM OF         MEAN             F       F
        SOURCE               D.F.    SQUARES       SQUARES          RATIO   PROB.

BETWEEN GROUPS                 2       3.4636        1.7318          .3440  .7095

WITHIN GROUPS                147     739.9840        5.0339

TOTAL                        149     743.4465


                                     STANDARD     STANDARD
GROUP        COUNT         MEAN     DEVIATION      ERROR       MINIMUM      MAXIMUM       95 PCT CONF INT FOR MEAN

Grp 1          50       24.0396      2.4208        .3425      19.1100      30.2500       23.3486 TO      24.7306
Grp 2          50       23.4026      2.3654        .3345      15.5000      31.9800       22.7206 TO      24.0850
Grp 3          50       23.6964      1.8888        .2667      18.5000      27.3000       23.1673 TO      24.2255

TOTAL         150       23.6998      2.2337        .1824      19.1100      31.9800       23.3402 TO      24.0700

       FIXED EFFECTS MODEL           2.2436        .1832                                 23.3476  TO     24.0716

      RANDOM EFFECTS MODEL                         .1832                                 23.1314  TO     24.6076

WARNING - BETWEEN COMPONENT VARIANCE IS NEGATIVE
          IT WAS REPLACED BY 0.0 IN COMPUTING ABOVE RANDOM EFFECTS MEASURES

RANDOM EFFECTS MODEL - ESTIMATE OF BETWEEN COMPONENT VARIANCE         -0.0660

Tests for Homogeneity of Variances

     Cochrans C = Max. Variance/Sum(Variances) =   .3912, P =  .435 (Approx.)
     Bartlett-Box F =                             1.697 , P =  .183
     Maximum Variance / Minimum Variance          1.642

      Variable  FDMM
   By Variable  EXP           experiment
```

TTNT grey/pr. water/fibre diameter

```
      Variable  FDMM
   By Variable  EXP          experiment

                        ANALYSIS OF VARIANCE P0820/pr. water/ fibre diameter

                                     SUM OF         MEAN              F      F
        SOURCE               D.F    SQUARES        SQUARES          RATIO  PROB.

BETWEEN GROUPS                 2     13.8046         6.9023          .2874  .7505

WITHIN GROUPS                147   3530.4296        24.0165

TOTAL                        149   3544.2342


                                   STANDARD   STANDARD
GROUP        COUNT        MEAN    DEVIATION    ERROR      MINIMUM     MAXIMUM      95 PCT CONF INT FOR MEAN

Grp 1           50     24.8980      5.8222      .8234     17.8400     53.4200     23.2443 TO    26.5537
Grp 2           50     25.5346      4.2136      .5959     19.8500     47.8400     24.4411 TO    26.8361
Grp 3           50     25.8484      4.5163      .6387     19.9000     41.1900     24.3820 TO    26.8289

TOTAL          150     25.4260      4.8772      .3982     17.8400     53.4200     24.6411 TO    26.2149

        FIXED EFFECTS MODEL       4.9007      .4001                              24.6352  TO    26.2168

       RANDOM EFFECTS MODEL                   .4001                              23 7063  TO    27 1457

WARNING - BETWEEN COMPONENT VARIANCE IS NEGATIVE
         IT WAS REPLACED BY 0.0 IN COMPUTING ABOVE RANDOM EFFECTS MEASURES

RANDOM EFFECTS MODEL - ESTIMATE OF BETWEEN COMPONENT VARIANCE        -0.3423


Tests for Homogeneity of Variances

     Cochrans C = Max. Variance/Sum(Variances) =  .4705, P =  .024 (Approx.)
     Bartlett-Box F =                            2.934 , P =  .053
     Maximum Variance / Minimum Variance         1.909
```

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14 Aug 90    1985 properties of geotextiles                                                                          Pag
12:58:23     University of Alberta

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      Variable  FDMM
   By Variable  EXP          experiment

                        ANALYSIS OF VARIANCE Q200/oil/fibre diameter

                                     SUM OF         MEAN              F      F
        SOURCE               D.F    SQUARES        SQUARES          RATIO  PROB.

BETWEEN GROUPS                 2     72.4138        36.2069         2.8321  .0621

WITHIN GROUPS                147   1879.3292        12.7846

TOTAL                        149   1951.7431


                                   STANDARD   STANDARD
GROUP        COUNT        MEAN    DEVIATION    ERROR      MINIMUM     MAXIMUM      95 PCT CONF INT FOR MEAN

Grp 1           50     29.7256      2.1043      .2976     24.5600     34.7100     29.1274 TO    30.3238
Grp 2           50     30.5136      3.5723      .5052     23.7900     39.7800     29.4984 TO    31.5288
Grp 3           50     31.4262      4.6005      .6506     18.5000     48.7500     30.1188 TO    32.7336

TOTAL          150     30.5552      3.6192      .2955     18.5000     48.7500     29.9712 TO    31.1391

        FIXED EFFECTS MODEL       3.5755      .2919                              29.9783  TO    31 1321

       RANDOM EFFECTS MODEL                   .4913                              28.4413  TO    32.6691

RANDOM EFFECTS MODEL - ESTIMATE OF BETWEEN COMPONENT VARIANCE         0.4684


Tests for Homogeneity of Variances

     Cochrans C = Max. Variance/Sum(Variances) =  .5516, P =  .000 (Approx.)
     Bartlett-Box F =                           13.555 , P =  .000
   . Maximum Variance / Minimum Variance         4.779



      Variable  FDMM
   By Variable  EXP          experiment

MULTIPLE RANGE TEST

SCHEFFE PROCEDURE
RANGES FOR THE 0.100 LEVEL -

         3.06    3.06

THE RANGES ABOVE ARE TABLE RANGES.
THE VALUE ACTUALLY COMPARED WITH MEAN(J)-MEAN(I) IS..
      2.5283 * RANGE * DSQRT(1/N(I) + 1/N(J))

   (*) DENOTES PAIRS OF GROUPS SIGNIFICANTLY DIFFERENT AT THE 0.100 LEVEL

                             G G G
                             r r r
                             p p p

     Mean       Group        1 2 3

   29.7256      Grp 1
   30.5136      Grp 2
   31.4262      Grp 3        *

  HOMOGENEOUS SUBSETS    (SUBSETS OF GROUPS, WHOSE HIGHEST AND LOWEST MEANS
                          DO NOT DIFFER BY MORE THAN THE SHORTEST
                          SIGNIFICANT RANGE FOR A SUBSET OF THAT SIZE)

SUBSET  1

GROUP        Grp 1         Grp 2
MEAN       29.7256       30.5136
- - - - - - - - - - - - - - - - -

SUBSET  2

GROUP        Grp 2         Grp 3
MEAN       30.5136       31.4262
- - - - - - - - - - - - - - - - -
```

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14 Aug 90    1989 properties of geotextiles
12:58:26     University of Alberta
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - O N E W A Y - - - - - - - - - - - - - - - - - - - - -

     Variable  FDIAM
  By Variable  EXP            experiment   TTNT white/oil/fibre diameter
                                   ANALYSIS OF VARIANCE

                                       SUM OF          MEAN              F        F
        SOURCE               D.F      SQUARES        SQUARES           RATIO    PROB.

BETWEEN GROUPS                 2       73.1439        36.5719         20.7784   .0000

WITHIN GROUPS                147      258.7343         1.7601

TOTAL                        149      331.8781

                                    STANDARD     STANDARD
GROUP         COUNT         MEAN   DEVIATION       ERROR       MINIMUM      MAXIMUM     95 PCT CONF INT FOR MEAN

Grp 1            50      21.7308      1.3958       .1974       17.5500      24.1600     21.3333 TO     22.1283
Grp 2            50      20.1006      1.1342       .1604       15.0100      23.0109     19.7783 TO     20.4228
Grp 3            50      21.3642      1.4276       .2019       19.5000      23.7900     20.9585 TO     21.7699

TOTAL           150      21.0652      1.4924       .1219       15.0100      24.1600     20.8244 TO     21.3060

       FIXED EFFECTS MODEL            1.3267       .1083                                20.8511 TO     21.2793

      RANDOM EFFECTS MODEL                         .4938                                18.9408 TO     23.1896

RANDOM EFFECTS MODEL - ESTIMATE OF BETWEEN COMPONENT VARIANCE         0.6962

Tests for Homogeneity of Variances

      Cochrans C = Max. Variance/Sum(Variances) =   .3860, P =  .505 (Approx.)
      Bartlett-Box F =                             1.492 , P =  .225
      Maximum Variance / Minimum Variance          1.584

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     Variable  FDIAM
  By Variable  EXP            experiment

MULTIPLE RANGE TEST

SCHEFFE PROCEDURE
RANGES FOR THE 0.100 LEVEL -

          3.06    3.06

THE RANGES ABOVE ARE TABLE RANGES.
THE VALUE ACTUALLY COMPARED WITH MEAN(J)-MEAN(I) IS..
        0.9381 * RANGE * DSQRT(1/N(I) + 1/N(J))

  (*) DENOTES PAIRS OF GROUPS SIGNIFICANTLY DIFFERENT AT THE 0.100 LEVEL

                              G G G
                              r r r
                              p p p

     Mean        Group        2 3 1

    20.1006      Grp 2
    21.3642      Grp 3        *
    21.7308      Grp 1        *

  HOMOGENEOUS SUBSETS     (SUBSETS OF GROUPS, WHOSE HIGHEST AND LOWEST MEANS
                           DO NOT DIFFER BY MORE THAN THE SHORTEST
                           SIGNIFICANT RANGE FOR A SUBSET OF THAT SIZE)

SUBSET  1

GROUP        Grp 2
MEAN        20.1006
- - - - - - - - - - -

SUBSET  2

GROUP        Grp 3        Grp 1
MEAN        21.3642      21.7308
- - - - - - - - - - - - - - - - - -
```

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     Variable  FDMM
  By Variable  EXP          experiment  P0820/oil/fibre diameter
                                    ANALYSIS OF VARIANCE

                                    SUM OF          MEAN              F        F
        SOURCE              D.F.    SQUARES         SQUARES           RATIO    PROB.

BETWEEN GROUPS                 2    777.5860        388.7930          12.9406  .0000

WITHIN GROUPS                147    4416.5277        30.0444

TOTAL                        149    5194.1135


                                     STANDARD     STANDARD
GROUP          COUNT       MEAN      DEVIATION    ERROR       MINIMUM      MAXIMUM       95 PCT CONF INT FOR MEAN

Grp 1             50     24.9790      5.8222       .8234      17.9400      53.6200        23.3243 TO     26.6337
Grp 2             50     24.1800      3.4785       .4919      15.6000      35.1000        23.1914 TO     25.1686
Grp 3             50     29.3870      6.6436       .9395      23.6000      62.0100        27.4990 TO     31.2750

TOTAL            150     26.1820      5.9042       .4821      15.6000      62.0100        25.2294 TO     27.1346

        FIXED EFFECTS MODEL           5.4813       .4476                                 25.2975  TO    27.0665

       RANDOM EFFECTS MODEL                       1.6100                                 19.2548  TO    33.1081

RANDOM EFFECTS MODEL - ESTIMATE OF BETWEEN COMPONENT VARIANCE          7.1750

Tests for Homogeneity of Variances

     Cochrans C = Max. Variance/Sum(Variances) =   .4897, P =  .010 (Approx.)
     Bartlett-Box F =                             9.818 , P =  .000
     Maximum Variance / Minimum Variance          3.648


     Variable  FDMM
  By Variable  EXP          experiment TTNT grey/oil fibre diameter
                                    ANALYSIS OF VARIANCE

                                    SUM OF          MEAN              F        F
        SOURCE              D.F.    SQUARES         SQUARES           RATIO    PROB

BETWEEN GROUPS                 2     12.1335         6.0666           1.2564   .2877

WITHIN GROUPS                147    709.8233         4.8287

TOTAL                        149    721.9568


                                     STANDARD     STANDARD
GROUP          COUNT       MEAN      DEVIATION    ERROR       MINIMUM      MAXIMUM       95 PCT CONF INT FOR MEAN

Grp 1             50     24.0396      2.4296       .3436      19.1100      29.2600        23.3491 TO     24.7301
Grp 2             50     23.3454      1.9761       .2795      20.2600      29.2500        22.7838 TO     23.9070
Grp 3             50     23.7432      2.1618       .3057      20.2800      31.2000        23.1288 TO     24.3576

TOTAL            150     23.7094      2.2012       .1797      19.1100      31.2000        23.3543 TO     24.0645

        FIXED EFFECTS MODEL           2.1974       .1794                                 23.3548  TO    24.0640

       RANDOM EFFECTS MODEL                        .2011                                 22.8441  TO    24.5747

RANDOM EFFECTS MODEL - ESTIMATE OF BETWEEN COMPONENT VARIANCE          0.0248

Tests for Homogeneity of Variances

     Cochrans C = Max. Variance/Sum(Variances) =   .4078, P =  .271 (Approx.)
     Bartlett-Box F =                             1.052 , P =  .349
     Maximum Variance / Minimum Variance          1.513


     Variable  FDMM
  By Variable  EXP          experiment

MULTIPLE RANGE TEST

SCHEFFE PROCEDURE
RANGES FOR THE 0.100 LEVEL -

          3.06   3.06

THE RANGES ABOVE ARE TABLE RANGES
THE VALUE ACTUALLY COMPARED WITH MEAN(J)-MEAN(I) IS .
      3.8758 * RANGE * DSQRT(1/N(I) + 1/N(J))

   (*) DENOTES PAIRS OF GROUPS SIGNIFICANTLY DIFFERENT AT THE 0.100 LEVEL

                             G G G
                             r r r
                             p p p

    Mean        Group        2 1 3

   24.1800      Grp 2
   24.9790      Grp 1
   29.3870      Grp 3        * *

  HOMOGENEOUS SUBSETS   (SUBSETS OF GROUPS, WHOSE HIGHEST AND LOWEST MEANS
                         DO NOT DIFFER BY MORE THAN THE SHORTEST
                         SIGNIFICANT RANGE FOR A SUBSET OF THAT SIZE)

SUBSET  1

GROUP       Grp 2         Grp 1
MEAN       24.1800       24.9790
- - - - - - - - - - - - - - - - -

SUBSET  2

GROUP       Grp 3
MEAN       29.3870
- - - - - - - - - - -
```

APPENDIX A-5 ENERGY DISPERSIVE X-RAY ANALYSIS OF P0820