Development of Transverse-Flow Capillary-Membrane Modules of the Modular and Block Types for Liquid Separation and Bioreactors

SE Domröse • DA Finch • RD Sanderson

Report to the Water Research Commission
by the
Institute for Polymer Science
University of Stellenbosch

WRC Report No 847/1/98

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EXECUTIVE SUMMARY

OBJECTIVES OF THE PROJECT

Development of cost effective membrane cartridge modules of up to $10m^2$
Development of multi-cartridge modules of up to $100m^2$
Development of manifolding for capillary membrane modules
Development of a transverse flow capillary membrane module

FUNCTION AND PURPOSE OF A MODULE.

A capillary membrane module is an important component of any membrane filtration and purification plant. Its main function is to house, locate, protect and secure the capillaries. It provides connections for product feed, concentrate and permeate and ensures that separate channels exist for the different streams, any mixing of which would render the module useless. Epoxy potting and encapsulation provides hydrodynamically sealed (watertight) and separate flow channels.

Ease of exchange, regeneration and flushing of membranes, ease of assembly and of dismantling of the module in actual field application are vital design features which will become obvious only under prolonged operating conditions.The module must be robust to withstand temperature fluctuation, pump cavitation or specially designed pressure pulsating and/or air sparging. Further, it must endure chemical cleaning and operator or system error without compromising the module integrity.

INTRODUCTION

A concise account is given of the research and development carried out during the period from 1 January 1994 to 31 December 1996 on the Water Research Commission contract K5/618/0/1 for the *Development of specialised Cross and Transverse Capillary Membrane Modules* for the large scale treatment of surface water to potable and sterile standards.

MOTIVATION

There is an ever increasing demand for potable water for human and industrial consumption, while the supply is diminishing, mainly due to growing population, pollution and agricultural use of potable water sources.

Water purification and recycling are very specialised areas of membrane separation techniques. For this very reason every effort should be made to practically apply research results and make them available for the advancement of knowledge and economic growth.

DESIGN CONCEPT

Only designs which are suitable for mass production and commercial application have been retained, others have only been kept as design studies for future reference. The design criteria applied to the designs were reliability and reproducibility at a consistant high quality. Semi-skilled staff must be able to produce modules. In short the maxim *DESIGN EXCELLENCE IS SIMPLICITY* has been applied. Proven design concepts tested in the laboratory or at pilot plants have been selected.

MODULE TYPES

The most economic module is the cartridge type, free of all fittings, which forms part of the manifold and which is covered by plant capital expenditure.

An obvious question is: Do we need a manifold? or, How can we simplify a water purification plant?

An answer to this can be twofold:

a) Multi-cartridge modules having enough cartridges housed in a module to make up the required membrane area for a plant, because the module has only one feed inlet, one permeate and one concentrate outlet, therefore no manifold is required to distribute the feed.

b) One large single module providing the required membrane area. For this reason the 200mm$^{\emptyset}$ module (18-25m^2 membrane area) has been developed, as it makes a manifold superfluous.

RESEARCH RESULTS

PRODUCTS

a) MULTI-CARTRIDGE MODULE

A three 50mm$^{\emptyset}$ cartridge capillary membrane module (3 x 1.5 =4.5m^2 membrane area) had been laboratory bench tested over an extended period of time and again successfully field tested at Mon Villa. Results are reported in other pilot plant studies.

b) 90mm$^{\emptyset}$ MODULE CARTRIDGE

Three 90mm$^{\emptyset}$ modules (3 x 5m^2 =15 m$^{2)}$, requiring a manifold, were installed and pilot plant tested at Mon Villa and are still operating after 23 months. Further field trials and pilot plants are operating with 6 modules at Suurbrak and Windhoek.

c) 200 mm$^{\emptyset}$ MODULE CARTRIDGE

A large 200$^{\emptyset}$mm module cartridge (18-25 m^2 membrane area) has been developed as it makes a manifold superfluous. This module has been bench tested and has exceeded all expectations. Delivery of pure water was measured at over 1000 litres per hour per m^2 at a transmembrane pressure of only 50 kPa. With the method developed and patented much larger modules are possible.

PATENT.

A patent, *Capillary Membrane Modules*, has been filed and granted for the epoxy encapsulation method, **SA Patent 96/1580**

DESIGN

Tank type modules

200mm$^{\emptyset}$ cartridges can be housed in a multi-cartridge or tank type module consisting of 3 ,7 ,19 , 37 or 55 cartridges, creating plants of up to 75, 175, 475, 925 or 1375m^2 membrane area respectively.

The implication and benefits are many:

- **Reduced plant costs**, because no manifold, less piping, fewer pressure gauges and less instrumentation are required.
- **Improved reliability** has been achieved which is very important for rural communities some distance away from service centres
- **Shorter plant operator training time has become possible**, because of streamlined plant design. An interactive multimedia computer program is being developed under WRC project No K5/728, which will be of great help in operator training.
- **Education** of a large cross section of people from various backgrounds takes place, making them more aware of, and interested in, water management and recycling by means of the abovementioned audiovisual method .
- **Mass production of axial flow capillary membrane modules** should be possible with semi skilled staff due to the complete tooling, moulds, machines and jigging of the manufacturing process.

3rd GENERATION TRANSVERSE FLOW CAPILLARY MEMBRANE MODULE

Due to extensive design studies and the making of handmade prototypes and mock-ups the 2nd Generation could be skipped, thereby preserving research funds. The costs of an injection mould for a complicated, scaled up spacer template with a support lattice are prohibitive and beyond the financial resources available. This latest design has an inner spacer reduced in size and complexity, with locating holes instead of grooves. It is completely epoxy encapsulated and hermetically sealed. These factors lend themselves to high quality, reliable and repeatable mass production of membrane modules.

CONCLUSION

Research results and products for the cartridge type capillary membrane modules have exceeded the objective and the anticipated industrialisation time. This was due to the fact that early in the contract period the objectives changed from those of a research project to those of a technological application, and emphasis was on the development of the 90 mm^{O} module.

Based on the success of the 3-cartridge type module and the experience gained, the design of the tank type module using either the 90^{O}mm or 200mm^{O} cartridges could be executed, allowing for units with a membrane area of 1000m^2 and more.

Development of the latest unique design transverse flow capillary membrane module will be finalised, patented, and manufacture will commence, in 1997. (K5/847)

The results are very positive and encouraging, which may be attributed to sustained and progressive research by a stable staff.

RECOMMENDATIONS

1) Capillary membranes should be truly geometrically round, not oval. Any deviation will result in a lower burst-pressure and assembly problems. To ensure that this does not happen, vacuum calibration should be applied during spinning.
2) Patent the 2nd and 3rd Generation transverse flow capillary membrane module method.
3) Fit an impeller to the tangential inlet flange of the 200mm^{O} module, positioned just above the capillary membrane module face. The feed stream will turn the impeller which in turn will block and unblock the lumen, thereby creating a pulsating feed which will reduce the forming of a boundary layer. As a consequence the membrane effectiveness is not reduced.
4) Manufacture membrane modules with Stainless Steel shrouds as, due to the thinner SST walls, this will increase the number of capillaries that can be packed into, and therefore the membrane area of, a module of the same size.
5) Manufacture tank-type modules in collaboration with an industrial partner which has expertise in SST tank maufacture.
6) Use surface modification techniques, developed by the tolerant membrane research team for increased hydrophilicity for low fouling membranes, to improve the polymer /epoxy bonding, and so allow for gluing by epoxy.

VISION

The above steps will make a significant contribution to providing water at the lowest possible cost to the consumer. A question still remains to be answered: How can this be applied to small informal settlements or disaster areas?

One solution would be to fully develop a low mass water purification plant skid mounted on a 1/2 ton bakkie and powered by diesel or petrol engines and operated at the point of requirement. The other extreme would be the development of large stationary tank-type module plants which , because of sheer size, will ensure economy of operation.

Overall context

For an overall context this report should be studied together with the:

- Multimedia computer program on capillary membrane modules.
- Pilot plant and field studies of capillary membrane modules.
- Skinless capillary membranes.

Safeguarding of intellectual property .

All developments in the areas for the axial flow and laboratory size transverse flow modules and manifolds are protected and covered by RSA Patents and some Namibia Patents. Work on the up-scaling of the transverse flow module is still ongoing and will continue in 1997. For various reasons a radically different solution had to be sought to be effective and acceptable for reliable commercial size transverse flow capillary membrane modules. This work is not yet protected by patents and therefore all detailed engineering drawings or methods which are included are to be treated as confidential.

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LIST OF ABBREVIATIONS

SST	Stainless steel
uPVC	unplasticized PolyVinyl Chloride
dia.	diameter
o	diameter
HDPE	High Density Polyethylene
UF	Ultrafiltration
MF	Microfiltration
NF	Nanofiltration
MMCO	Molecular Mass Cut Off
RO	Reverse Osmosis
CAD	Computer Aided Design
Caddie	CAD system from Caddie Computer Aided Design (Pty) Ltd
DWG	Drawing
PP	polypropylene
MEK	Methyl Ethyl Ketone
SOLID WORKS	3 Dimensional Solid Modelling CAD system.

CHAPTER 1: MODULE DESIGN

1.1 DESIGN CONCEPT

A simple design concept has been applied to capillary-membrane modules to enable them to be easily machined, manufactured, repaired and serviced. Off-the-shelf standard components were used to increase reliability and durability at reasonable cost. For good module design, the following should apply: "*Design genius is simplicity!*" It should be understood that simplicity is not to be confused with inferior design or quality, but refers to a design which is functional and results in a reliable, long lasting, useful and user-friendly product.

Figure 1.1 shows an assembled 200mm$^{\emptyset}$ capillary membrane module. The epoxy-encapsulated module head with the O-Rings and potted capillaries are shown in the foreground, while the permeate outlet and the clamp saddle are visible in the midsection.

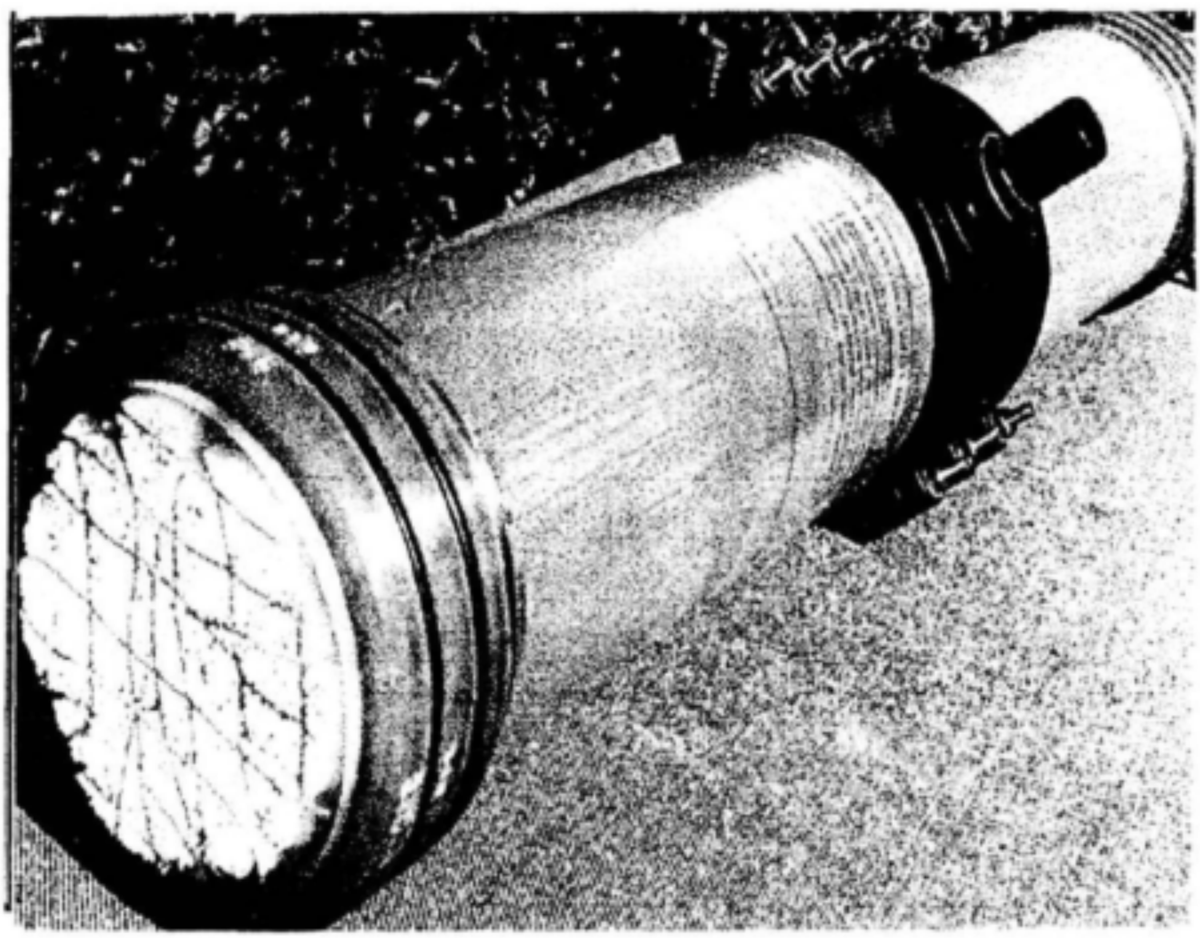


FIGURE 1.1 : AN ASSEMBLED 200mm$^{\emptyset}$ CAPILLARY MEMBRANE MODULE

1.2 DESIGN REQUIREMENTS

To meet the capillary membrane module requirements successfully, the design must meet minimum criteria, which can be summarised as follows: A module must secure, position and protect membranes against damage, and provide the connections for feed, permeate and concentrate flow. These three flow channels must seal hermetically because any leakage, for example, between feed and permeate, renders a module useless. It must also make provision for regeneration, be easy to connect and dismantle and easy to repair, even in field pilot plant operation.

1.3 DESIGN EXPERIENCE AND FUTURE DEVELOPMENT

With the experience gained over several years in membrane module design, questions as to the future direction of the research and development had to be asked and answers provided. These answers were not to be intuitive, but based on solid facts and values which could be quantitatively and qualitatively determined. Hence the following graphs were compiled, as shown in Figures 1.2 and 1.3.

1.4 PACKING DENSITY

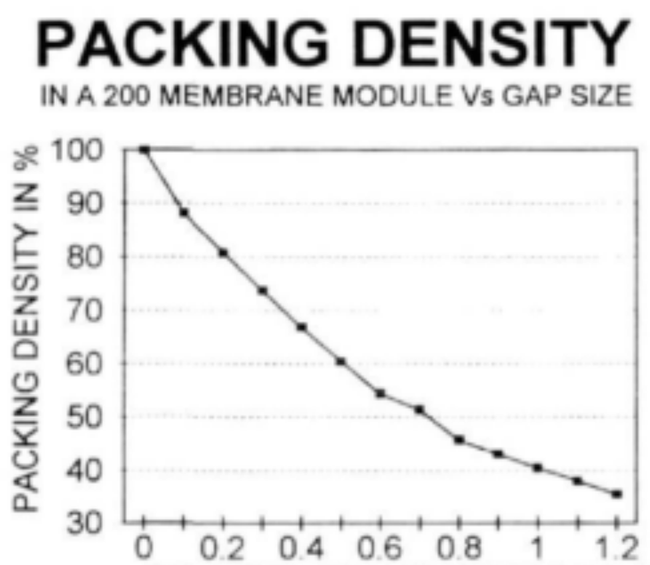


FIGURE 1.2: PACKING DENSITY OF CAPILLARIES IN A MODULE

Figure 1.2 shows the relationship between the gap, or distance, between the individual capillaries in a module and the number of capillaries which can be packed into a module shroud. With increasing gap size , the number of capillaries which can be fitted decreases, ie the packing density is reduced. A gap between the capillaries is essential for the epoxy to flow in between the capillaries and form a seal to keep the feed separated from the permeate and the concentrate. A balance must be maintained between a high packing density and the process conditions of epoxy encapsulation. Factors such as epoxy viscosity, centrifugal casting force and ambient temperature as well as the configuration of the epoxy flow channels, have to be taken into account.

1.5 NUMBER OF CAPILLARIES

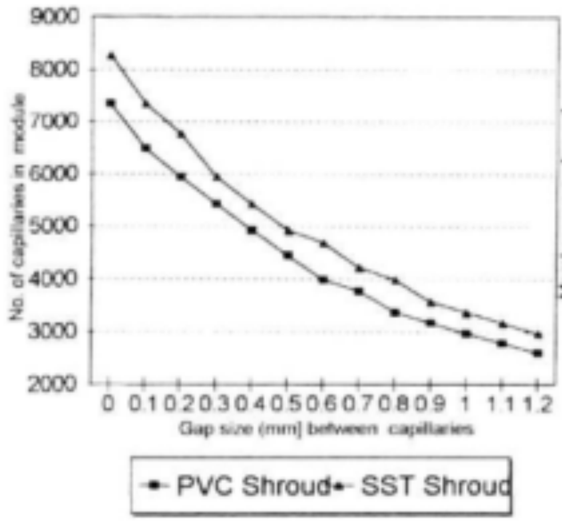
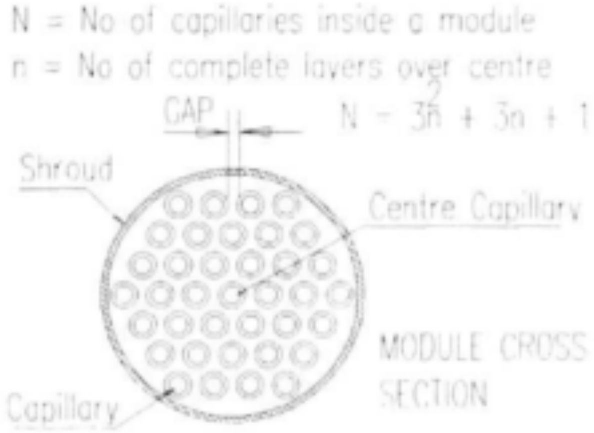


FIGURE 1.3 :NUMBER OF CAPILLARIES IN A MODULE

A further factor which influences the number of capillaries which can be housed in a shroud and subsequently influences the capillary module membrane area, is the wall thickness of the shroud. The graph shown in Figure 1.3 illustrates that a stainless steel (SST) shroud will, because of its thinner wall section, hold more capillaries than an unplasticised polyvinychloride (uPVC) shroud. An advantage of a SST shroud is, however, that such a module can be sterilised and operated at temperatures higher than 55^{O} C, which is the maximum operating temperature of a uPVC shroud. Wherever possible, standard components are used, to make the modules as cost effective as possible without compromising on quality and performance.

1.6 ARRANGEMENT OF CAPILLARIES



Theoretical spacing of capillaries and calculation of their number in a module

FIGURE 1.4: CAPILLARY PATTERN

The number of capillaries which can be housed in a module is calculated according to standard formulae used for calculating the number of strands in a steel wire rope. The packing pattern is arranged around a centre capillary, around which the rest of the capillaries are grouped to form concentric circular layers. Other packing arrangements are also possible, with either two or three capillaries in the centre.

Figure 1.4 is a schematic representation of the number of capillaries which can be packed into a module shroud varies according to the size of the gap between the individual capillaries. There are, however, practical limitations to the minimum gap size. Too small a gap will result in dry spots i.e. areas into which no potting epoxy can flow. These in turn, will cause leakage between feed and permeate, and render the module non-functional or useless for water purification.

1.7 MASS DISTRIBUTION

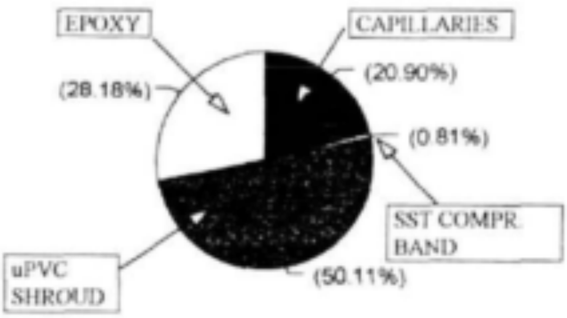


FIGURE 1.5: MASS RELATIONSHIP

A mass value relationship in an axial flow capillary membrane module, for a 200mm$^{\varnothing}$ capillary membrane module, has been established, and is shown in Figure 1.5. The capillaries contribute 20.9% by mass, but constitutes the highest portion of the cost. This is because polyether sulphone costs about R150.00 per kg while processed uPVC, from which the module shroud is produced, costs approx. R25.00 per kg.

If a SST shroud were to be used the cost would be even higher, although it would be offset by the fact that SST has a thinner wall section and more capillaries could be packed into the module than into a uPVC shroud with the same outside diameter. Epoxy resin for the encapsulation and potting costs about R50.00 per kg.

1.8 VALUE ENGINEERING

A value engineering study was undertaken to establish the best module configuration. For this purpose the following factors were considered:

Single or multi-cartridge type module
Economy of manufacture
Use of standard components
Module arrangement in a plant
Ease of module exchange and replacement
Integration of module with manifold
Material strength for static and dynamic loads
Packing density of capillaries
Membrane area
Module cost
Reliability of module
Ergonomics and ease of plant operation
Plant operator training
Plant maintenance

1.9 DESIGN DETAILS OF A 90mm$^{\varnothing}$ MODULE

Figure 1.6 shows the design details of a 90mm$^{\varnothing}$ capillary membrane module. Capillaries are inside the shroud and sealed at each end with epoxy. Epoxy is between the capillaries and also between the capillaries and the inside of the shroud. As the epoxy shrinks, it is forced tightly against the outer wall of the shroud, thereby forming a hermetic seal. Further, the epoxy also extends around the end of the shroud, therefore encapsulating the module end completely. On the inside of the shroud the epoxy reaches up higher than it does on the outside. The importance of this can be seen in the further improvements to the 200mm$^{\varnothing}$ module. (See figure 1.7).

ONE END OF A COMPLETE POTTED AND ENCAPSULATED
90mm DIAMETER CAPILLARY MEMBRANE MODULE

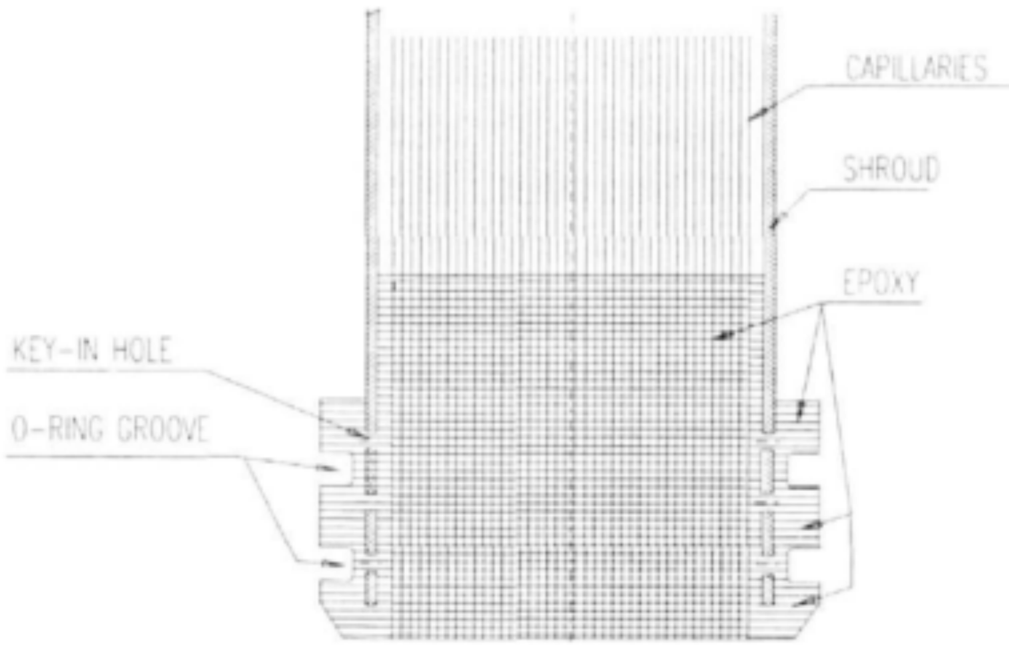


FIGURE 1.6: 90mm$^{\emptyset}$ CAPILLARY MEMBRANE MODULE.

The module head has a lead-in chamfer to assist in fitting the module into a manifold or for assembling of the end caps.
There are two O-Ring grooves to receive O-Rings to seal the module to the plant system. For this purpose the O-Ring cross section has been specified to be large to compensate for ovality and generous manufacturing tolerances.

1.10 DESIGN DETAILS OF A 200mm$^{\emptyset}$ MODULE

Further design improvements to the 200mm$^{\emptyset}$ module, over the 90$^{\emptyset}$ module were:

1. Two internal silicon rubber seals were added (now also incorporated into the 90mm$^{\emptyset}$ module, as was done in the case of the 40mm$^{\emptyset}$ and 50mm$^{\emptyset}$ models).

2. The height of the epoxy head was extended on the outside by providing a shoulder to take a SST compression band, to prevent material creep of the uPVC shroud in the module-head interface-section. This is required if the module is operated at a high shell pressure. This applies if the feed for the capillary membrane module is taken directly from a high-pressure process-stream and the recycling of the feed is not required. By adding the steel

compression band, fitted in the critical module head interface areas, the module can then operate without a pressure-reducing valve and without a feed-circulation pump. The capillaries, in this instance, would not collapse under the following conditions: feed inlet pressure of up to 500 kPa, concentrate pressure of 440 kPa and permeate pressure 420 kPa, giving an average transmembrane pressure of 50 kPa.

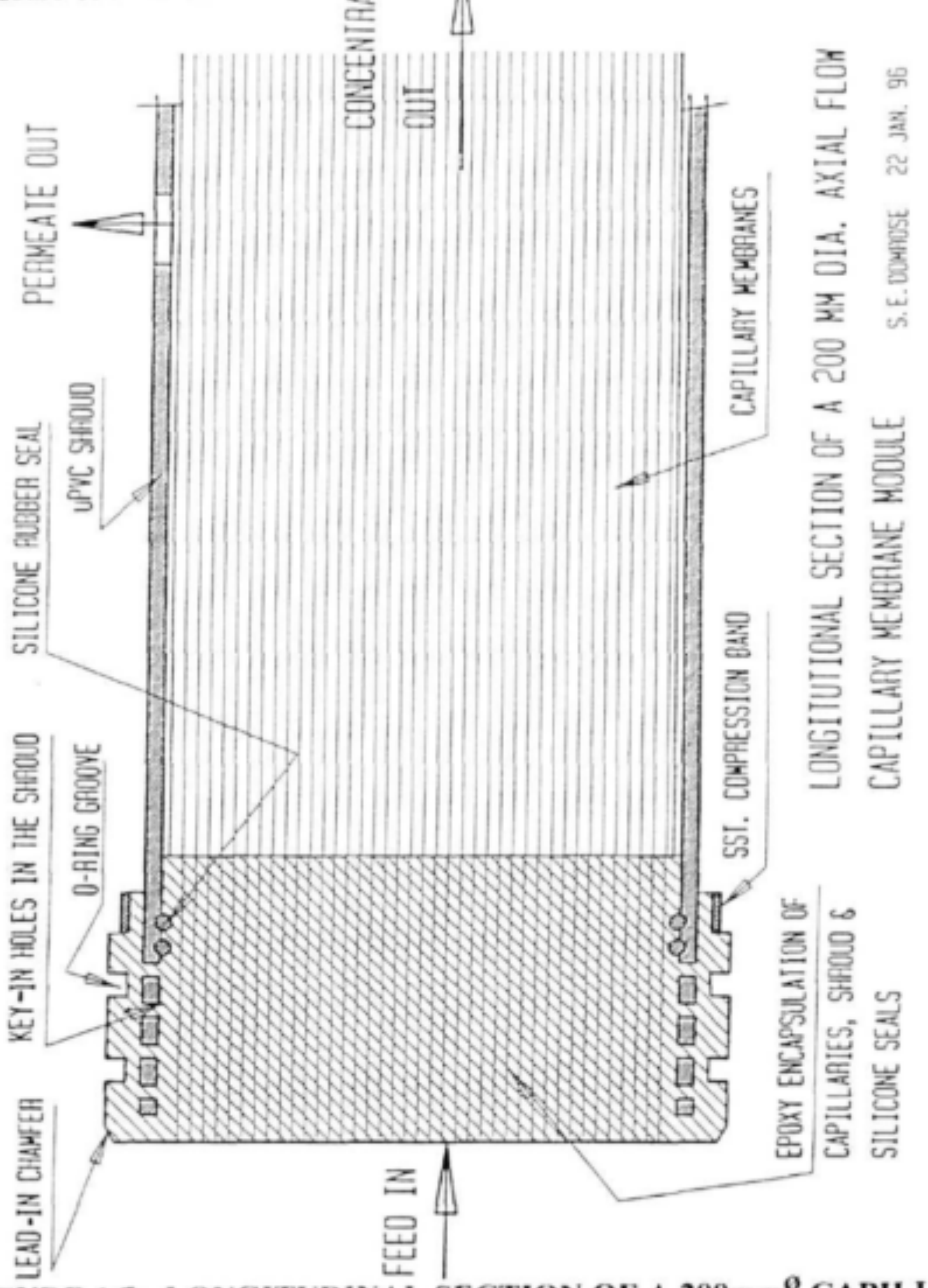


FIGURE 1.7: LONGITUDINAL SECTION OF A 200mm$^{\emptyset}$ CAPILLARY MEMBRANE MODULE

1.11 MULTI-CARTRIDGE MODULES

The most economical type of module is the cartridge type, free of all fittings. All fittings are part of the manifold, and are thus included in plant capital expenditure.

Obvious questions are therefore: Do we need a manifold? and How can we simplify a water purification plant?

Answers to these may be twofold:

a) Multi-cartridge modules are manufactured, having enough cartridges housed in a module, to make up the required membrane area for a plant. Because the module has only one feed inlet, one permeate outlet and one concentrate outlet, no manifold is required to distribute the feed.

b) The provision of the required membrane area in one large single module - The 200^Ø mm module (18-25 m^2 membrane area) has been developed for this purpose, as it makes a manifold superfluous. With the method developed and patented, much larger modules are also possible. For instance a module of 400^Ø mm would have a membrane area of 80 to 100 m^2.

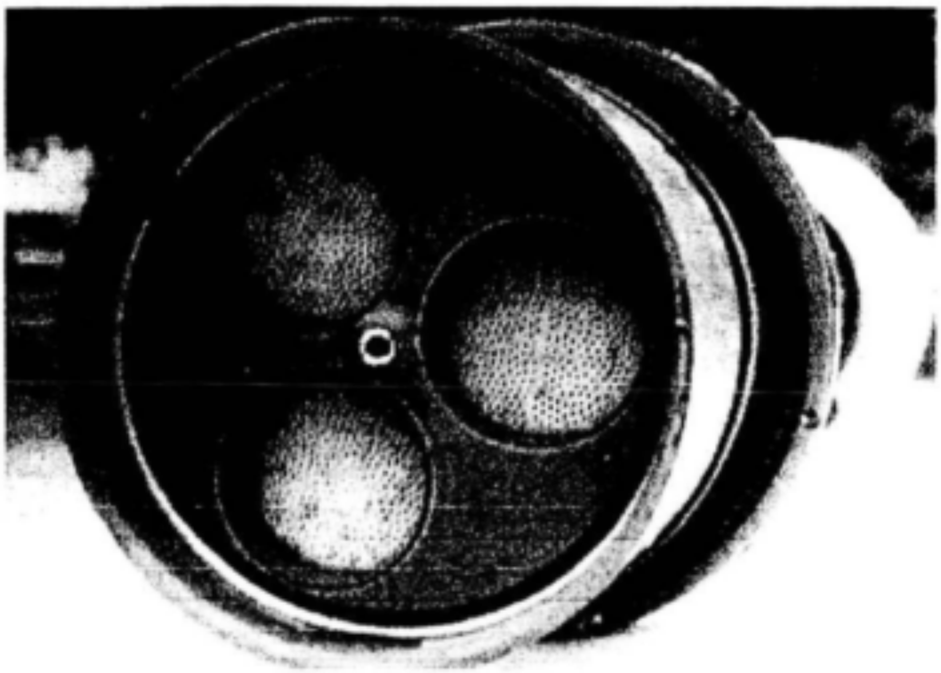


FIGURE 1.8: MULTI-CARTRIDGE MODULE WITH 3x50mmØ CARTRIDGES

A multi-cartridge module, as shown in Figure 1.8, consisting of three 50mm^Ø capillary membrane cartridges (3 x 1.5 = 4.5m^2 membrane area) has been laboratory bench-tested over an extended period of time and again successfully field-tested at Mon Villa. Based on the results of the tests, the multi-cartridge

module shown in Figure 1.13 could later be designed. Figure 1.8 also shows the stainless steel circlip securing the cartridges in the module shroud.
In the centre of the tube sheet is a helical jacking thread insert, required to facilitate dismantling of the module. Figure 1.9 shows the tangential inlet flange which ensures an across-the-face feed in a multi-cartridge module. Tangential feed is necessary because the capillary tubes become blocked by particles if direct feed is used. The tangential feed creates a vortex, which can easily be observed through the clear end of the flange, especially at the start up when there are air bubbles trapped in the system.

FIGURE I.9: MULTI-CARTRIDGE MODULE TANGENTIAL INLET FLANGE (CLEAR END, TO OBSERVE THE FEED VORTEX)

The 50mm$^{\varnothing}$ module was replaced, first by one 90mm$^{\varnothing}$ capillary membrane module and later by three 90mm$^{\varnothing}$ modules ($3 \times 5m^2 = 15\ m^2$), requiring a manifold. These modules have been in use for more than 23 months at Mon Villa. Further field trials and pilot plants are currently operating at various locations. 200mm$^{\varnothing}$ cartridges can also be housed in a multi-cartridge or tank-type module consisting of 3, 7, 19, 37 or 55 cartridges, creating plants of up to 75, 175, 475, 925 or 1375m^2 membrane area respectively.

When a cartridge is used in a multi cartridge system the module shroud need not function as a container or vessel as is the case with a single module. It is, however, preferable if the shroud is made from an expanded metal or other lattice-type material which is strong enough to allow for the insertion of the cartridge into the tube sheet, and able to overcome a slight pressure when it is pushed past the O-Rings into the tube sheet.

FIGURE 1.10: CAPILLARY MEMBRANE MODULE
WITH LATTICE TYPE SHROUD

The flow of product (permeate) is also enhanced when an open shroud as shown in Figure 1.10 is used.

3.12 FUTURE PROJECTIONS FOR MULTI-CARTRIDGE TANK-TYPE CAPILLARY MEMBRANE MODULE PERFORMANCE.

Tables 1.1 and 1.2 give estimates of future tank-type capillary membrane module performance.

No of cartridges	3	7	19	37	55
Total membrane area (m^2)	15	35	95	185	275
Estimated feed (m^3/h)	11	26	71	138	206
Estimated feed velocity (m/s)	0.67	0.67	0.67	0.67	0.67
Est.trans-membrane pressure(kPa)	55	55	55	55	55
Estimated delivery (ℓ/h)	825	1925	5225	10175	15125

TABLE 1.1: SPECIFICATIONS FOR 90mm$^{\emptyset}$ MULTI-CARTRIDGE OR TANK-TYPE MODULES

No of cartridges	3	7	19	37	55
Total membrane area (m^2)	60	140	380	740	1100
Estimated feed (m^3/h)	45	105	285	555	825
Estimated feed velocity (m/s)	0.67	0.67	0.67	0.67	0.67
Est.trans-membrane pressure (kPa)	55	55	55	55	55
Estimated delivery (ℓ /h)	3300	7700	20900	40700	60500

TABLE 1.2: TABLE OF SPECIFICATION FOR 200mm$^{\emptyset}$ MULTI-CARTRIDGE OR TANK-TYPE MODULES

Even larger membrane areas could be achieved if 400mm$^{\emptyset}$ cartridges were to be used in multi-cartridge modules. In fact this would increase the membrane area fourfold, when compared with a 200mm$^{\emptyset}$ cartridge module.

1.13 MULTI-CARTRIDGE TANK TYPE MEMBRANE MODULE

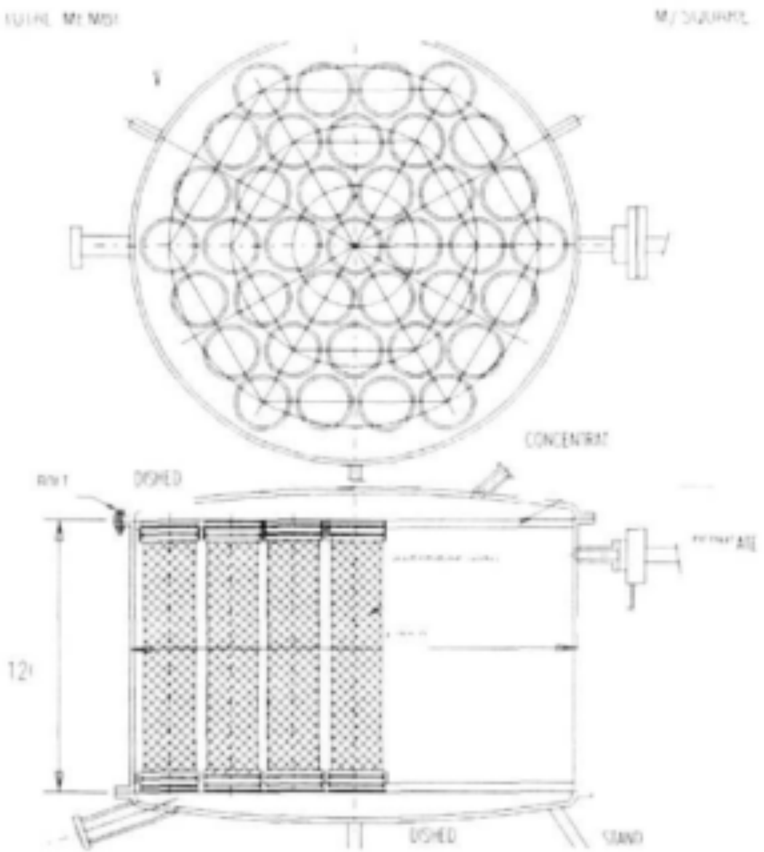


FIGURE 1.13: ASSEMBLY DRAWING OF A MULTI-CARTRIDGE MODULE WITH 37 CARTRIDGES OF 200mm$^{\emptyset}$

As can be seen from Table 1.2 and the module drawing in Figure 1.7, a multi-cartridge module or tank-type module with 55 cartridges, each 200mm$^{\emptyset}$ as illustrated in Figure 1.13, has a total membrane area of 1100m^2 and a tank diameter of less than 2000mm$^{\emptyset}$. This clearly demonstrates how compact these modules are - they require very little space compared with plant layouts in series or parallel. Backflushing of these large membrane areas is very important. Units have therefore been developed which employ servo-actuators to create wave forms, with sharp peaks, to clean the membrane from any boundary-layer build-up during backflushing.

1.14 LUMEN VS SHELL-FEED METHOD

Further space saving and an increase in membrane area in a module are obtained if the capillary membranes are shell-fed instead of lumen-fed. If a typical capillary membrane, as shown in Figure 1.14, with a cross section of 1.8mm outside diameter and 1.3mm inside diameter (1.8/1.3) is considered, then an increase of 38% in the membrane area is achieved by having the membrane skin on the outside instead of on the inside bore or lumen.

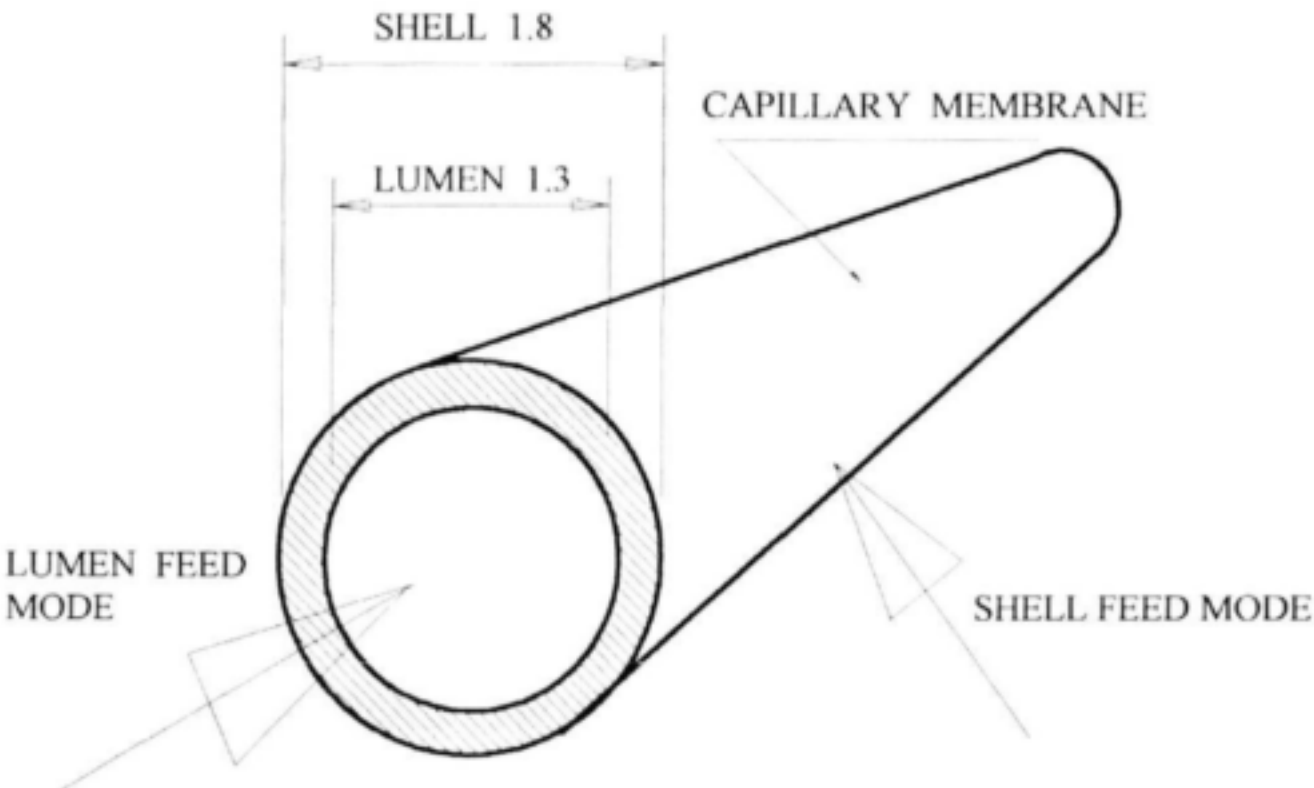


FIGURE 1.14: CAPILLARY MEMBRANE

CHAPTER 2
MANIFOLDS FOR CAPILLARY MEMBRANE MODULES

The purpose of a manifold is to connect many modules. In this case, the aim is to connect many modules to a common feed supply, and to optimise the process. This will lead to a reduction in the plant cost and eventually the price of the product water. Plant down-time is minimised if the manifold design is such that membrane modules can be easily fitted, dismantled or replaced. Once the capillary membrane modules have reached the end of their useful life, they are replaced by new ones, using the same manifold. The manifold is a reusable capital item, forming part of the plant, which has pressure gauges connected to it to measure the feed and flow conditions through the modules, as well as the control valves.

2.1 TYPES OF MANIFOLD:

PARALLEL

A number of modules can be connected in parallel to a manifold. The module ends protrude into the manifold, so that the feed flows across the face of the capillaries. The cross section of the manifold must be calculated to ensure that an equal amount of flow is directed through each module. Inertia effects of the water also plays an important role in module design. See Figures 2.1 and 2.2.

FIGURE 2.1: PARALLEL ARRANGEMENT OF MODULES IN A MANIFOLD

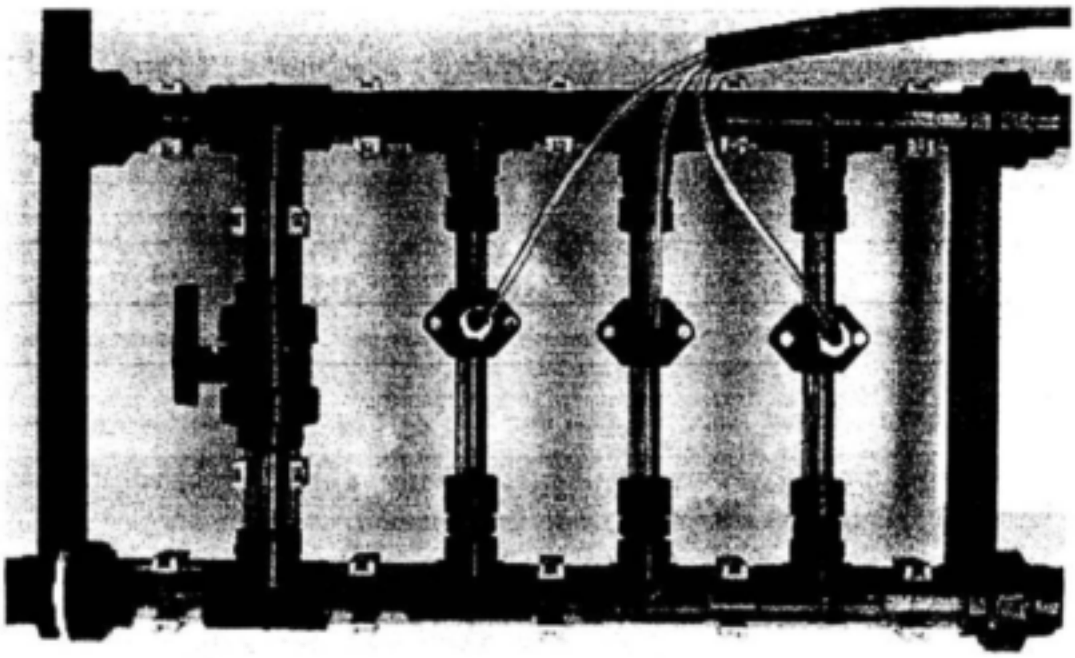


FIGURE 2.2: A PARALLEL FLOW MANIFOLD WITH 3 MODULES

In series

A number of modules can be connected in series to a manifold, as shown in Figure 2.3. This is a very simple design but has the disadvantage that the last module in the series receives the least feed, while the first module receives the most. Therefore, the first module operates efficiently while those which follow operate with decreasing efficiency.

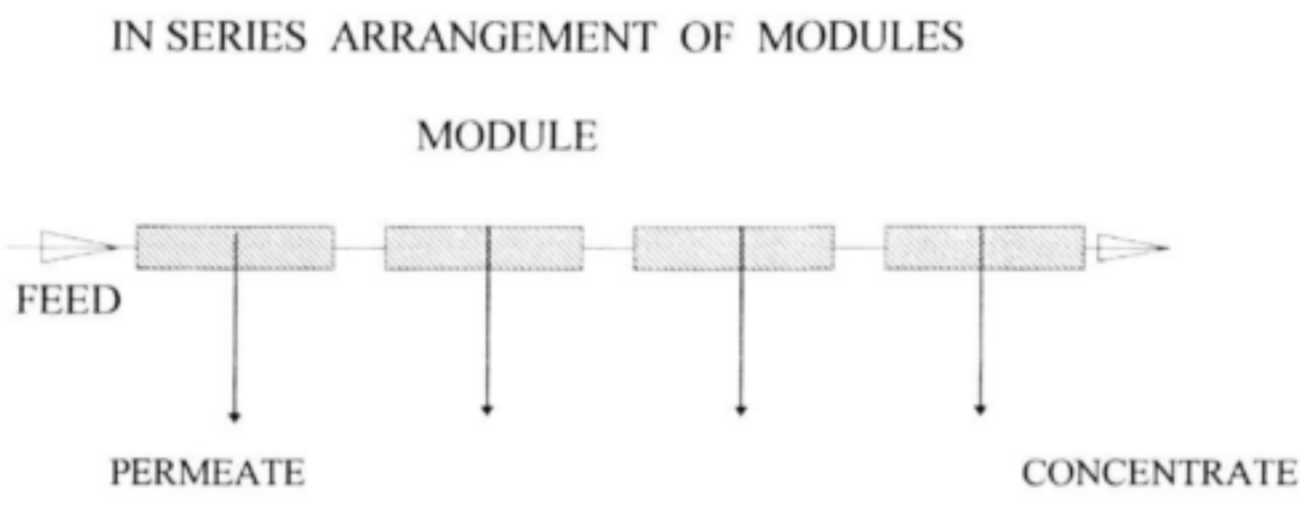


FIGURE 2.3 : MODULES CONNECTED IN SERIES

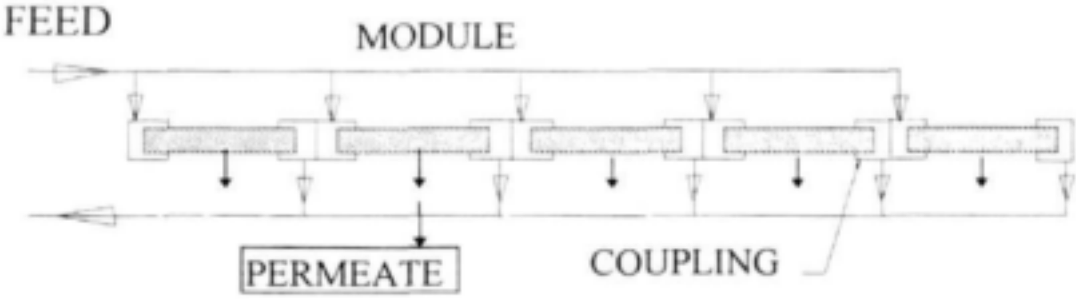


FIGURE 2.4: MODULES CONNECTED COMPENSATED-IN-SERIES

Compensated-in-series
Compensated-in-series is a combination of parallel and in-series connections (see Figure 2.4) to compensate for the diminishing feed stream with increasing distance of the module from the feed pump in an in-series arrangement. By this method an equal feed is provided to each module .

2.2 INLET-HOUSING

A single capillary membrane module can be connected to the process feed stream via the module endcap which takes on the function of a manifold or feed inlet housing.

2.3 INCORPORATED MANIFOLD

Multi-cartridge capillary membrane modules have a built-in manifold which forms part of the module housing or endcap as shown in Figure 1.9, 1.10 and 1.13

2.3 CASCADE ARRANGEMENT

For process plants with many modules a cascade arrangement is important to ensure that there is an equal feed supply to each module, as shown in Figure 2.5.

CASCADE ARRANGEMENT OF MODULES

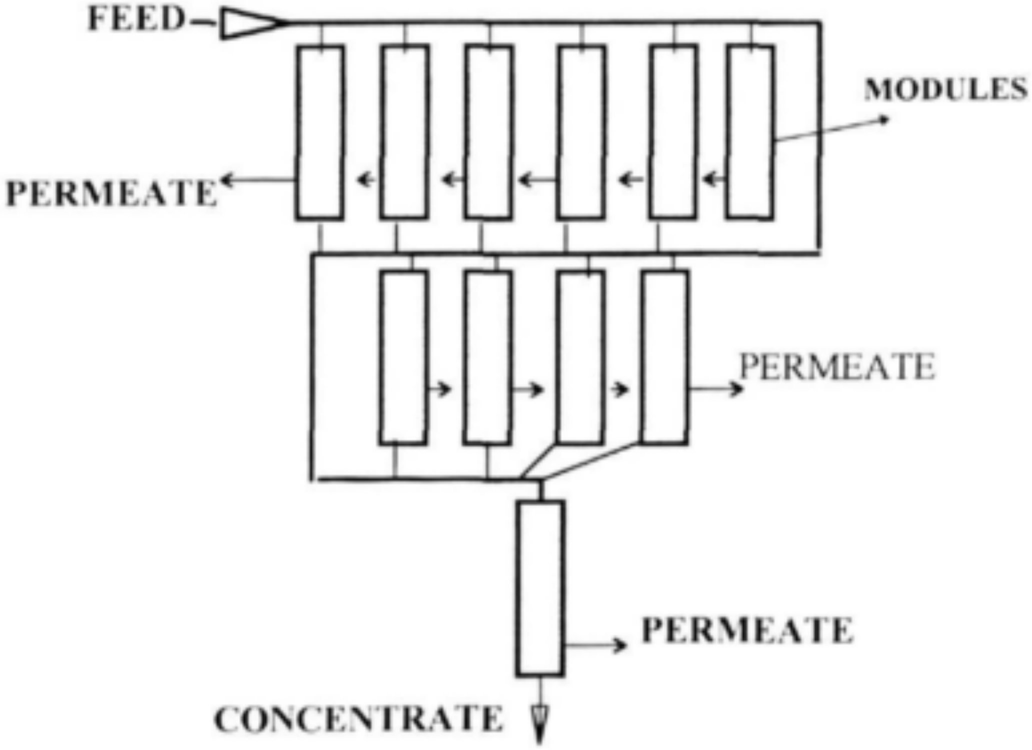


FIGURE 2.5 CASCADE ARRANGEMENT OF MODULES

2.5 DEAD END FLOW

This arrangement should be avoided as it could easily lead, depending on feed water quality, to blockage of the entrance of the capillary bores in the membrane module. Particles in the feed stream tend to block the capillaries, because the feed flows in a direction axial to the capillaries.

2.6 ACROSS-THE-FACE FLOW

The feed flows at 90^0 to the capillary module axis and any particles in the feed are swept over the capillary bores.

FIGURE-2.6 ACROSS - THE- FACE FLOW DETAIL

CHAPTER 3
MANUFACTURE OF AXIAL FLOW CAPILLARY MEMBRANE MODULE

3.1 MAKING UP OF CAPILLARY MEMBRANE BUNDLES .

The are made up into bundles to facilitate handling. The number of capillaries in a bundle is counted or weighed, then the bundle is held for trimming in a sleeve to protect the capillaries from damage during the manufacturing process. A bundle of capillaries is inserted into a protective PP (polypropylene) Netlon® sleeve. This is done by first stretching the protective sleeve over a thin walled tube and inserting the capillary bundle, held temporarily together with elastic bands, into the tube and then rolling the sleeve over the capillaries while pushing the capillaries through the tube.

For the 90mm^{O} capillary membrane module one bundle is used, while seven bundles are used for the 200mm^{O} module, as shown in Figure 3.1. These bundles of capillaries are kept together in one outer sleeve. The reason for having a number of bundles in the

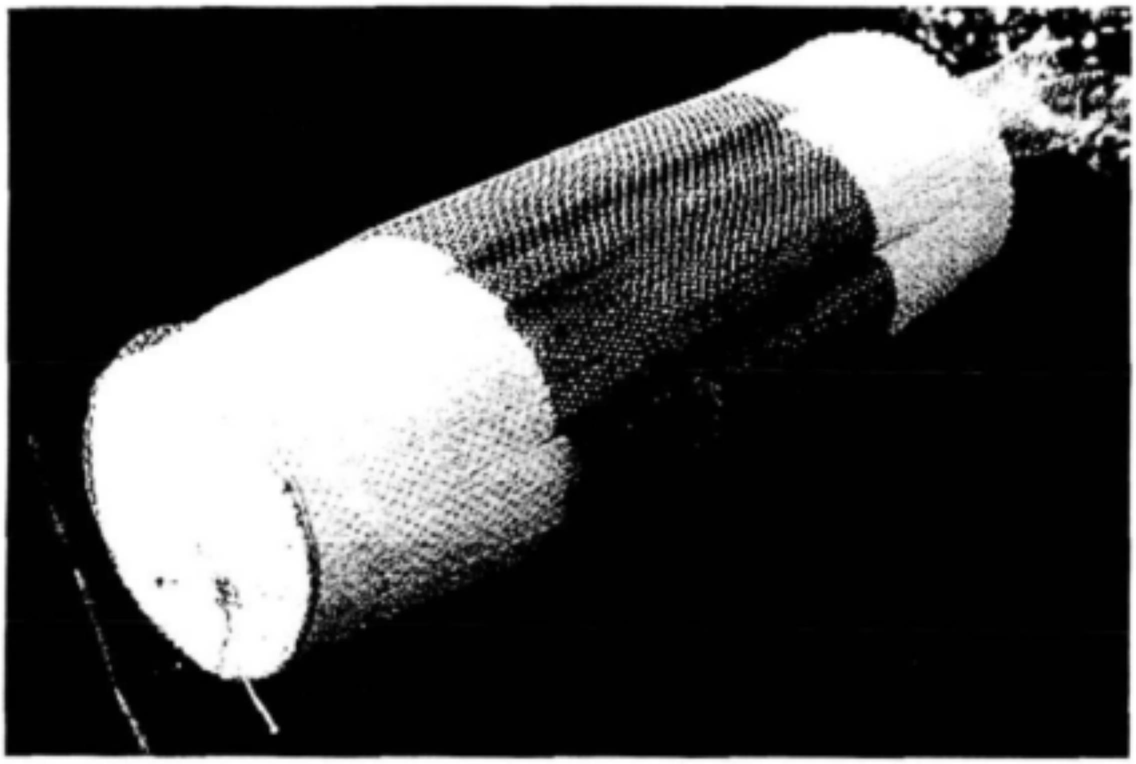


FIGURE 3.1 CAPILLARY BUNDLES HELD IN SEVEN NETLON SLEEVES AND SECURED IN ONE OUTER NET .

200^{0} mm module is to create flow channels for backwashing of the module. If only one large bundle is used, it might lead to reduced flow in the centre region during backwashing, resulting in the build-up of boundary layers, thereby reducing the permeate flux. From the extensive evaluation data recorded at water purification plants we are able to predict a suitable bundle size.

3.2 SEALING OF THE ENDS OF THE CAPILLARIES IN A BUNDLE

To prevent the epoxy blocking the insides of the capillaries during centrifugal casting, which would hinder flow of the feed, a method by which to seal the ends of the capillaries in such a way that this did not happen was required. A quick setting epoxy resin was poured into a silicon rubber cup. The bundle of vertically positioned capillaries was dipped into this. Due to the capillary action, resin is drawn up inside the capillaries for a short distance, thereby blocking the lumen.

Later in the manufacturing process this part was machined off, thereby opening all the lumens.

Once one end of the module had been encapsulated, the process was be repeated for the other end.

3.3 SHROUDS

Shrouds are produced from uPVC pipes, class 6. The latter denotes a working pressure of up to 600 kPa. These have the thinnest wall section, hence more capillaries can be packed into the shroud. A stainless steel shroud is even better as it has an even thinner wall section than the uPVC pipes and can operate at temperatures above 100 ^{0} C (a uPVC shroud is limited to 45^{0} C).

Machining, cutting to length, drilling of the key-in holes, permeate outlet holes and chamfering and deburring are easier and faster in uPVC than in stainless steel. Besides these advantages, the cost of uPVC is much lower then that of SST. The shroud must be free of burrs because they could damage the capillaries during the module assembly. For drilling of the key-in holes a jig is used to space the holes equally and in a staggered pattern. The present jig is made from plastic with pressed-in steel drill bushes. For mass production this should be replaced with a steel drill jig and hardened steel guide drill bushes. Other machines used were a lathe with a large diameter spindle bore, a drill press, cutting-off saws and machine and hand tools.

Bonding of the module ends, encapsulation and potting epoxy resin to the shroud must be strong, flexible long lasting and provide a hermetic seal in the module to keep the feed separate from the permeate.

Stainless steel and uPVC are suitable, but polyolefins are not. In the case of the latter there is poor adhesion and a good bond is not formed.
Alternate materials for the shroud are GRP (glass reinforced plastic) or the engineering polymers PA (nylon), PSU (polysulfone) and PPO (polphenyleneoxide), among others with operating temperatures above 100^{0}C. Large quantities of shrouds would be needed to justify the high tooling costs of producing the shrouds from these engineering polymers.

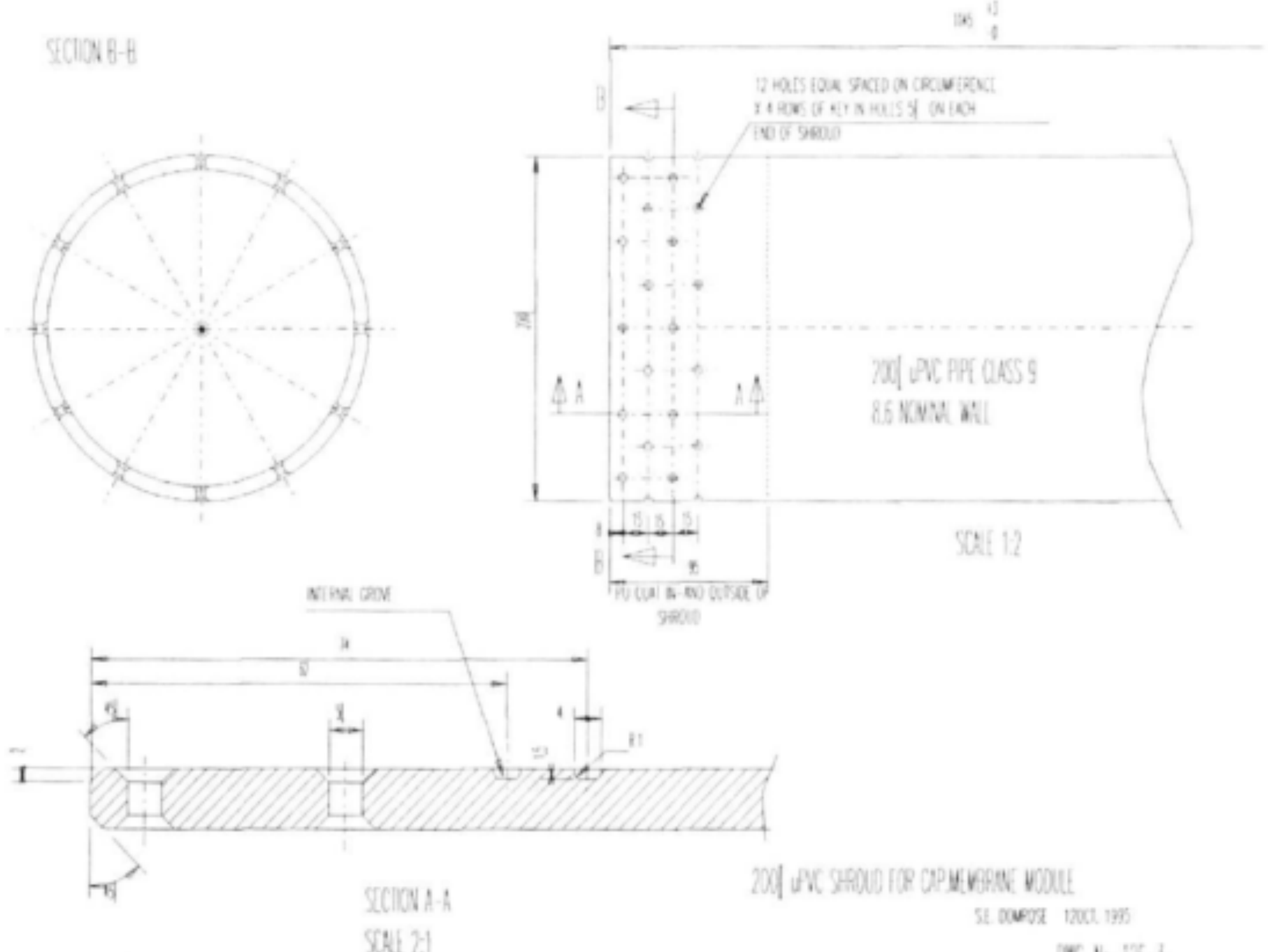


FIGURE 3.2 DETAIL DWG SHOWING MACHINING DETAILS OF A 200mm$^{\varnothing}$ uPVC SHROUD

Machining details of a 200$^{\varnothing}$ mm shroud are shown in the drawing in Figure 3.2, as well as the staggered positions of the key-in holes, arranged in columns and rows. The holes on the inside and outside, as well as on the shroud ends, were chamfered to remove any sharp edges which might damage the capillaries and also to avoid a shearing off of the epoxy in the key-in holes should any longitudinal movement occur. The two grooves seen in section A-A are for the silicon sealing rings. Drilling of the key-in holes is shown in Figure 3.3 and 3.4.

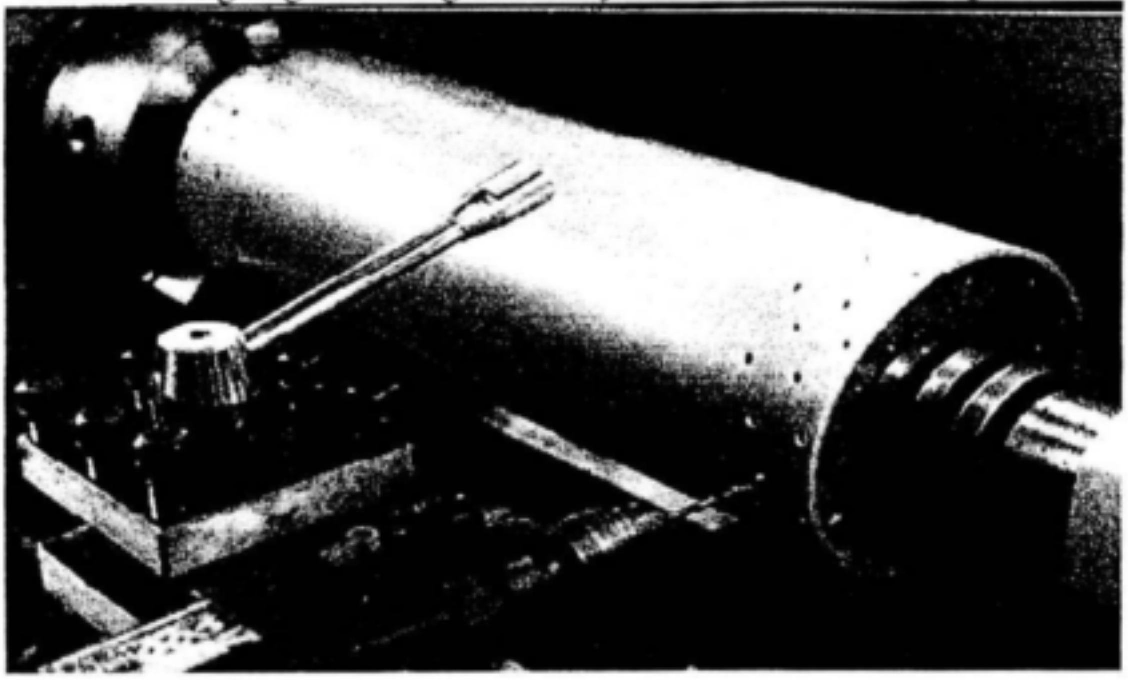


FIGURE 3.3 DRILLING OF KEY-IN HOLES IN A CENTRE GAP LATHE OF A SHROUD FOR A 200 ⁰ MM CAPILLARY MEMBRANE MODULE

FIGURE 3.4 SHROUD DETAIL WITH FOUR ROWS OF KEY-IN HOLES ARRANGED IN A STAGGERED PATTERN

3.4 SURFACE PREPARATION OF EPOXY CONTACT AREA

Justification for the additional application of a primer coat to the bonding areas is confirmed by the following research results. Results of tests carried out on 25mm diameter samples for epoxy potting, recorded graphically in Figures 3.5 to 3.9, show that polyurethane (PUR) priming of the bonding surfaces gave the best overall physical performance results. Prior to priming, the surface must be roughened with sandpaper and degreased. Besides bond strength, force and shear, the flexibility of the bonding interface is very important. This is because during handling, transportation, installation and operation of the module under dynamic conditions, shocks or impacts occur which must be absorbed without compromising the bonding integrity between the epoxy, uPVC shroud and the capillary membranes. Modules housed in a polymer shroud are particularly subject to deformation and must remain functional after returning to the original shape.

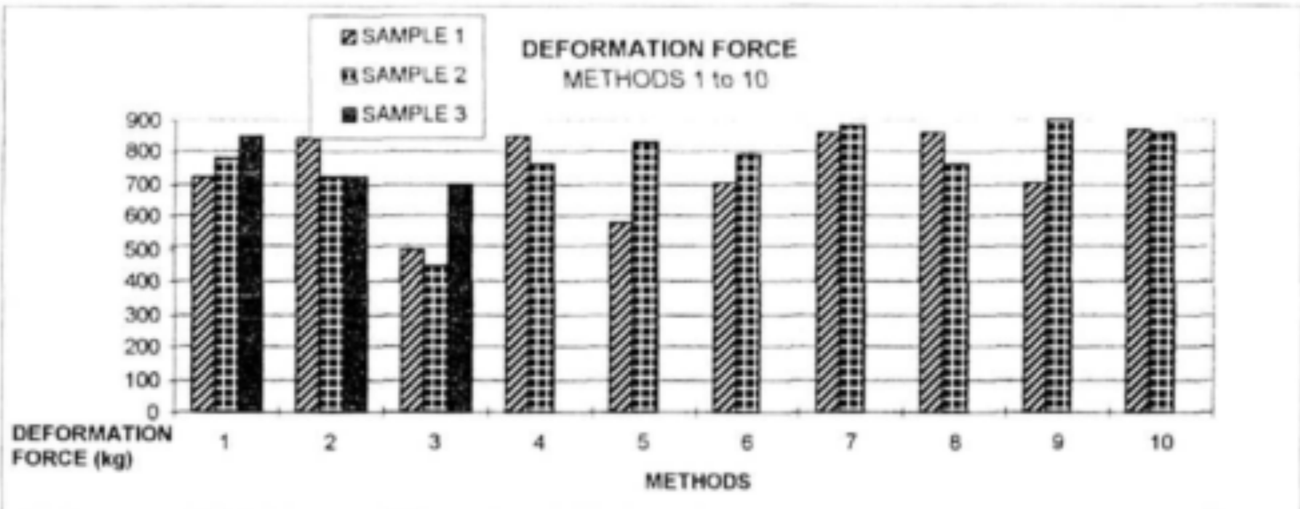


FIGURE 3.5: FORCE REQUIRED TO DEFORM A MODULE END PERPENDICULAR TO ITS AXIS, UNTIL IT CRACKS.

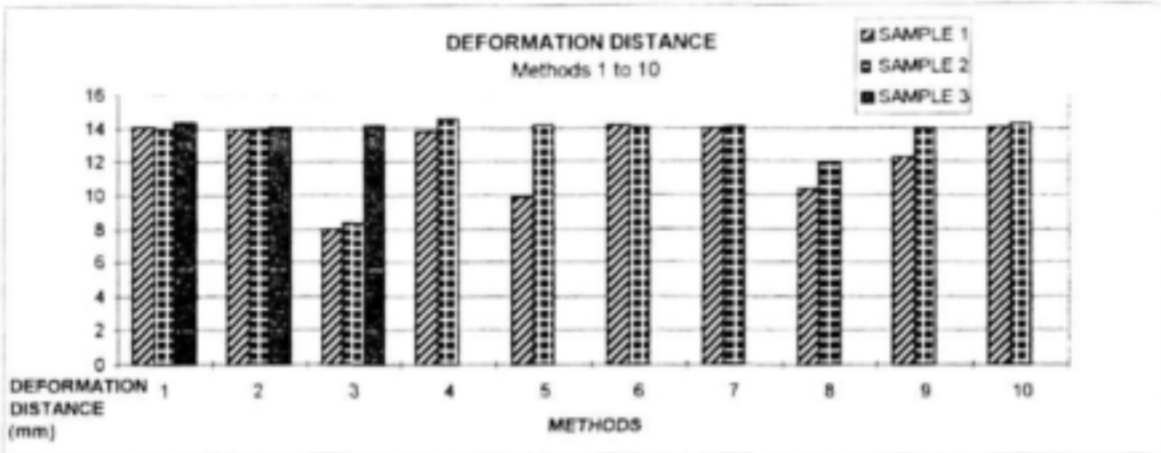


FIGURE 3.6 : DEFORMATION DISTANCE IN RELATIONSHIP TO THE DEFORMATION FORCE (REFER FIGURE 3.5)

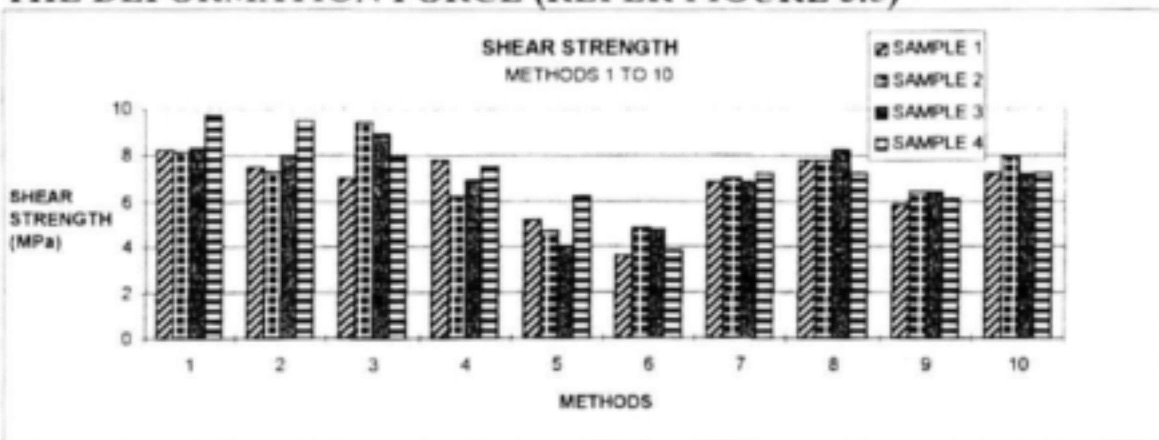


FIGURE 3.7:SHEAR STRENGTH REQUIRED TO DISLODGE AN EPOXY POTTED PLUG

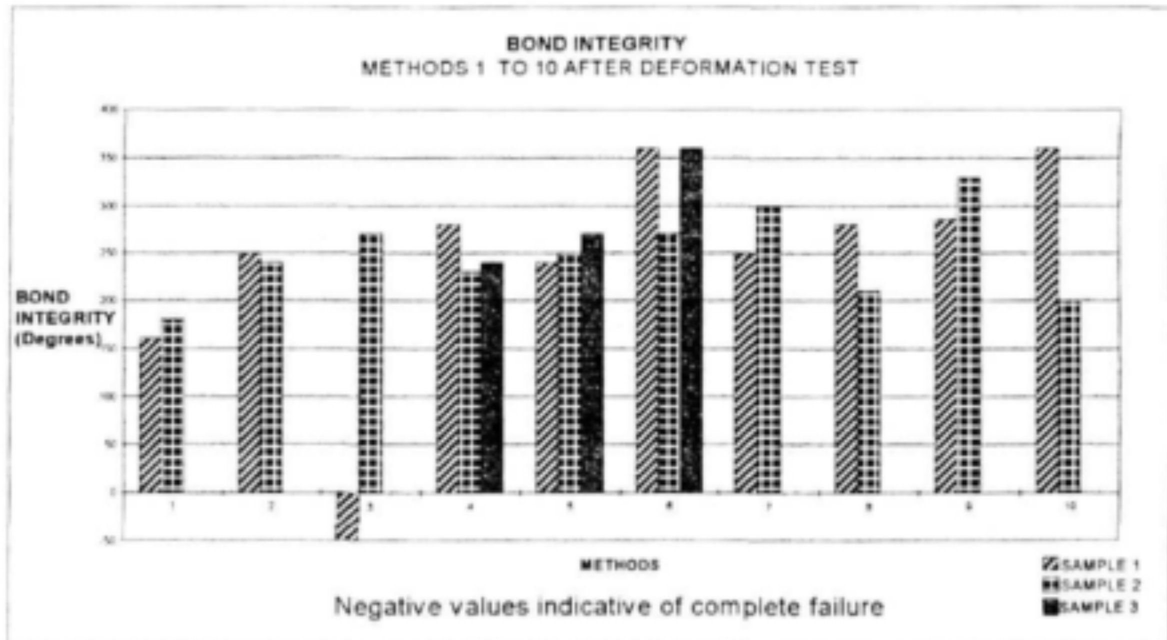


FIGURE 3.8: BOND INTEGRITY AFTER 5 MM DEFORMATION .

3.5 EXPERIMENTAL DETAILS ON THE PRE-TREATMENTS OF TEST SPECIMENS

METHOD 1: No pre-treatment

METHOD 2: No pre-treatment

METHOD 3: Cleaning of bonding areas with MEK

METHOD 4: Cleaning with MEK and priming with PUR, drying for 0.5 hr before epoxy casting .

METHOD 5: Clean with MEK and prime with PUR, dry for 4 hr before epoxy casting .

METHOD 6: Clean with MEK and prime with PUR, dry for 24 hr before epoxy casting .

METHOD 7: Prime with a mixture of 8g Dichloromethane (CH_2 CL_2)and 6 drops Hexamethyldisilazan ($(CH_3)_3$ SiNHSi $(CH_3)_3$

METHOD 8: Prime with a mixture of 8g Dichloromethane (CH_2 CL_2) and 4 drops Isocyanate (Urea 641B)

METHOD 9: Prime with a mixture of 8g Dichloromethane (CH_2 CL_2) and 5drops Silane (Shell Ind. grade)

METHOD 10: Prime with a mixture of 8g Dichloromethane (CH_2 CL_2) and 5 drops Dimethyl-Dichlorosilan

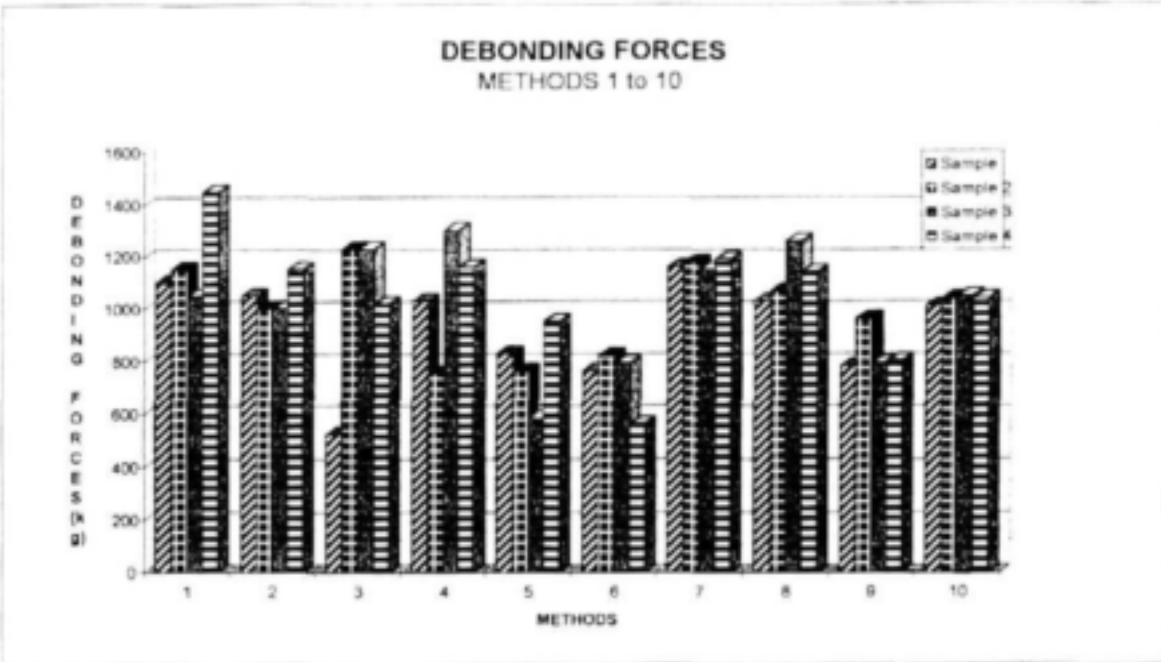


FIGURE 3 9: DEBONDING FORCES REQUIRED IN A LONGITUDINAL DIRECTION TO SHIFT AN EPOXY POTTED PLUG FROM A 40 ^{O} mm SHROUD WITH NO KEY-IN HOLES .

A compromise must be reached between sheer shear strength, debonding forces, deformation characteristics and bond integrity. It is for this reason that the surface preparation method No 6 is mostly suitable, because it results in a good balance of strength, flexibility and rigidity .

3.6 MOULD FOR EPOXY ENCAPSULATION

A detailed engineering drawing of the mould assembled for epoxy encapsulation is shown in Figure 3.10. Various components of the mould are shown and their functions described. The body holds the forming segments, locking segments and base plates in position. This is secured by 6 hexagonal bolts, nuts and washers. The forming segments are split to release the undercuts which form the O-ring grooves. The same applies to the locking segments which receive the O-ring in the mould assembly to prevent any epoxy from leaking from the mould, but at the same time must let air escape to vent the mould. All parts of the mould are machined from HDPE (High Density Polyethylene) because this material releases easily from the cast epoxy and the mould is easy to clean for the next casting. Figure 3.11 shows the dismantled epoxy encapsulation mould.

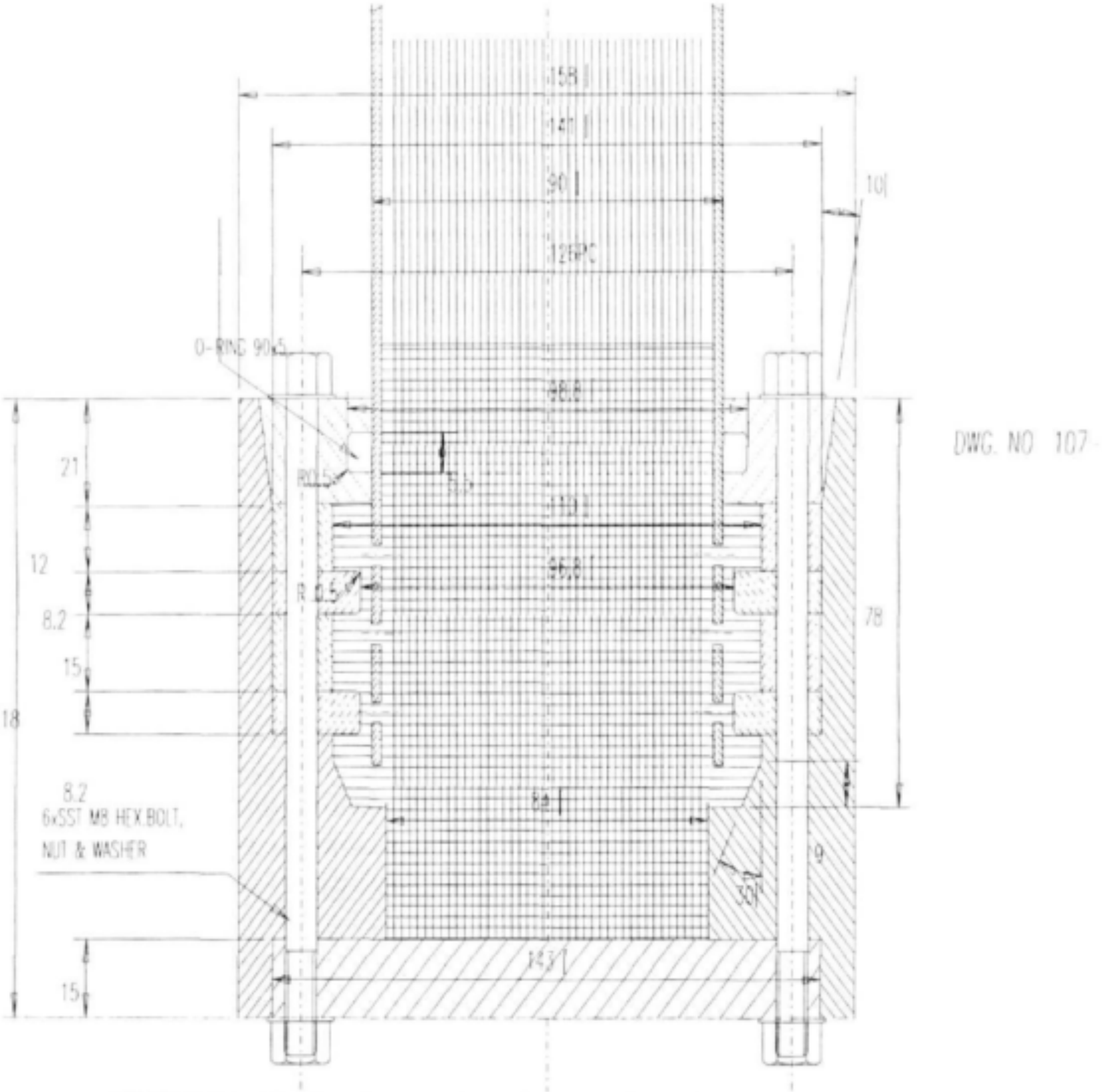


FIGURE.3.10: **Detailed engineering drawing of the mould assembly with the capillary membrane module head shown in position**

FIGURE 3.11: PHOTOGRAPH OF CENTRIFUGAL CASTING MOULD COMPONENTS.

3.7 MODULE ASSEMBLY FOR CASTING

A primer is applied to the epoxy interface area after surface preparation. Counted bundles of capillaries held together in a netting sleeve are inserted and positioned in the shroud. Figure 3.12 shows a pack of capillaries ready for insertion into a shroud The epoxy casting mould is then fitted and the module prepared for centrifugal epoxy potting and encapsulation. Membralok N°4 resin is mixed in the correct ratio, at a suitable temperature, and poured into the reservoir of the casting mould. This is followed by potting and encapsulation.

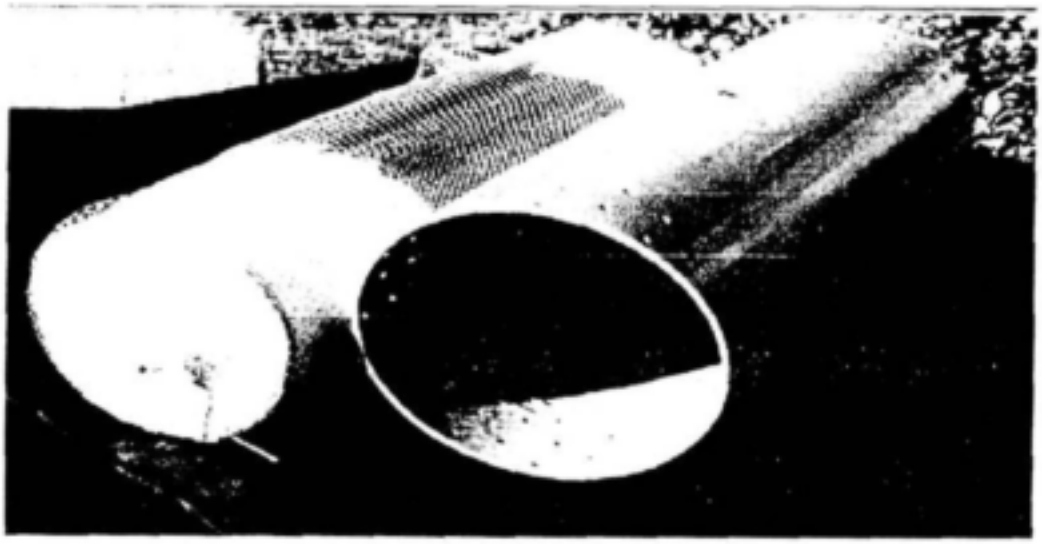


FIGURE 3.12: PACK OF CAPILLARIES READY FOR INSERTION INTO A SHROUD.

3.8 EPOXY RESIN

The epoxy resin fulfills a very important function, namely the sealing of all the flow channels and encapsulation of the capillaries and the shroud. The epoxy must therefore partially penetrate the capillary wall, as well as fill all the gaps between the capillaries and bond well to the shroud. From the point of processing it must flow easily, gel and cure as fast as possible, without generating high exothermic temperatures. This is critical, especially in larger epoxy encapsulations where a mass of over 5 kg is used. Further requirements are machinability during the slicing the module ends to open the capillaries, and machining the module to length. ***Membralok No 4*** epoxy was developed together with ***PAC CHEM*** [1]for this purpose. A and B components must be mixed in the correct ratio, within a short time without unnecessarily entrapping air. The ambient temperature must be controlled as it influences the viscosity of the epoxy resin.

3.9 EPOXY ENCAPSULATION

Epoxy encapsulation is a very important step in the module manufacturing process. Potting and encapsulation are done effected under high centrifugal force to expel any air bubbles present in the resin and also to ensure that the resin penetrates into all the small gaps between the individual capillaries. From the following equation it can be seen that the centrifugal force (G force) is a product of the speed in revolutions per second, expressed as the angular frequency, and the radius. The mass of the required epoxy is determined by the module size and can be considered it as a constant, leaving the radius and angular frequency as variables.

$$G_{FORCE} = m\ \omega^2\ r$$

ω = angular frequency; $\omega = 2\pi n$
m = mass of epoxy in kg
n = revolutions per second
r = radius in metres

Figures 3.13 and 3.14 show the epoxy encapsulation in progress as well as details of the jig holding the capillary membrane module, mould and epoxy reservoir in position.

[1] PAK CHEM (Pty) Ltd, Address: Pa hem Cape Town

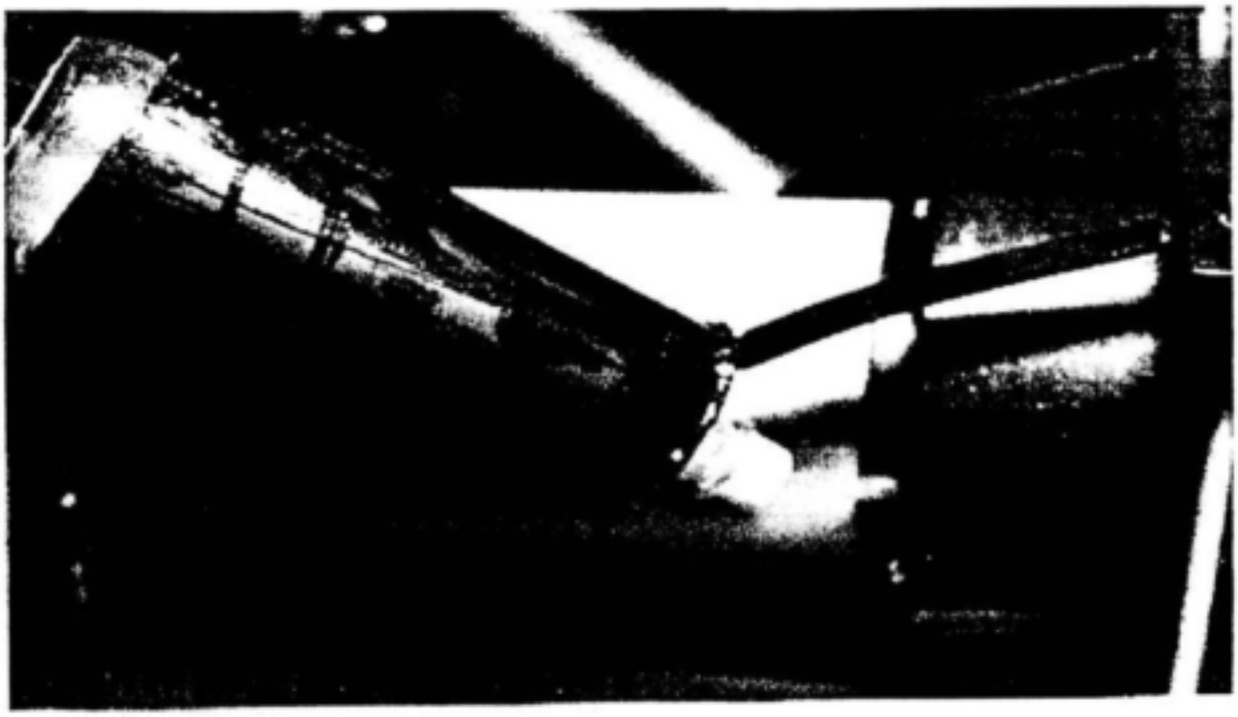


FIGURE 3.13 : CLOSE-UP PHOTO OF THE CASTING MOULD, EPOXY RESERVOIR AND FLEXIBLE RESIN FEEDING PIPE .

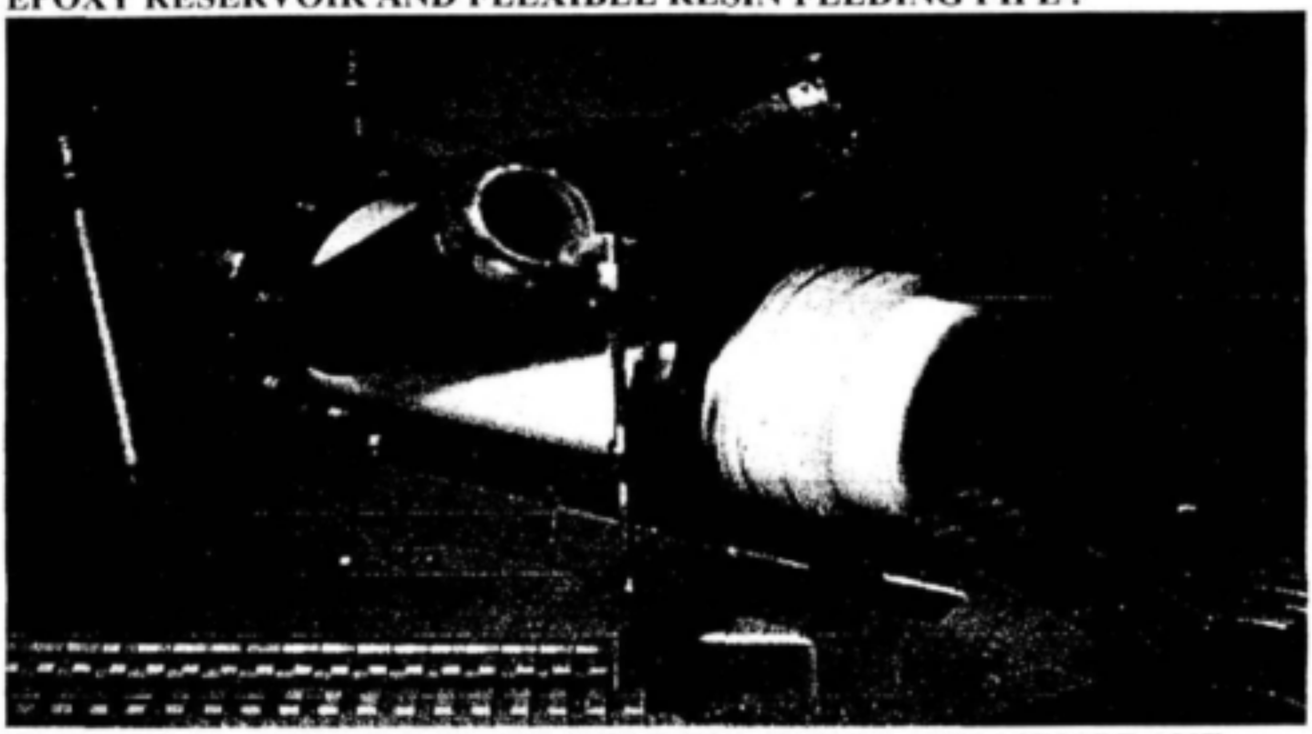


FIGURE 3.14 : DETAILS OF JIG HOLDING CAPILLARY MEMBRANE MODULE

and securing of it to the machine table of a horizontal boring mill. High centrifugal forces of 100 rpm are generated, and therefore all parts must be securely clamped to prevent accidents. Any loose parts would become very dangerous missiles! Cutting-off and slicing of the capillary module ends completes the manufacture, which is followed by the assembly of the permeate outlet.

3.10 CENTRIFUGAL FORCE EPOXY CASTING MACHINE .

For generating centrifugal forces for void-free casting of epoxy-encapsulated capillary modules, three types of method are available:

3.11 HORIZONTAL FIXED ARM MACHINES:

Here the module is clamped in a horizontal position to the rotating arm of the casting machine. A reservoir holds the epoxy resin and is connected with a flexible hose to the casting mould which is fitted to the module to be cast. The reservoir must have a venting hole to the atmosphere to allow epoxy resin to flow to the module during centrifugal casting. Once the machine is set in motion, the arm rotates around its central axis horizontally. At this stage the resin flows from the reservoir into the casting mould, filling the cavity between the module and the mould, taking on the shape of the mould and thereby forming the module's epoxy-encapsulated head. The centrifugal force must be maintained until the resin has gelled, or set or cured, to such an extent that no further movement is possible, i.e. the resin cannot run back to empty the mould or wet the capillaries beyond the intended point, which would be a disadvantage Both ends of the module can be cast simultaneously. A very basic machine for epoxy encapsulation of small capillary-membrane modules is shown in Figure 3.15.

FIGURE 3.15: HORIZONTAL CENTRIFUGAL CASTING MACHINE .

3.12 VERTICAL FIXED ARM MACHINE:

The same concept used in the horizontal fixed arm machine method applies, except that the rotation takes place around the centre axis in the vertical plane. Here more than one arm can be attached to the machine, fixed next to one another. This means that more than one module can be encapsulated at a time. A safety cage placed around the rotating parts reduces the air friction during casting because after the initial inertia the air inside it will also rotate at the speed of the mould. Again, the centrifugal force must be maintained until the epoxy is set. As with the horizontal machine, one or both ends can be cast simultaneously.

3.13 SWING ARM MACHINE :

This is a combination of aspects of the previous two methods. Modules to be cast are mounted in a vertical position onto the swing arms, which number three or four or more. Above the mould is the epoxy reservoir. One end of all the modules are cast at the same time. When the machine is switched on, the arms start to lift, with increasing speed, until the modules are in a horizontal position. Two important actions occur: the radius increases as the arm moves through an arc of 70° and, consequently, the centrifugal force increases.
As soon as the epoxy resin has been forced into the mould and all the air is expelled, the machine can be switched off. This is because the modules come to a standstill in a vertical position and it does not matter that the resin has not yet set, as the resin remains in the same, correct, position. The modules together with the mould can now be removed from the machine and another set of modules fitted for casting. Utilisation of the machine is so much higher, because the time for forcing the resin into the mould and expelling all the air is about 1 hour. compared to 4-6 hours for the horizontal and vertical casting methods.

3.14 SLICING OF EPOXY ENCAPSULATED MODULE ENDS

The drawing in figure 3.16 and the photo in Figure 3.17 shows what the module looks like after casting and indicates the portion that has to be cut off and sliced in a lathe. See also Figure 3.18.
First a slice is sawn off with a wood saw; this is a part of the piece of which the capillary ends and bores were blocked with quick-setting epoxy. The module is then clamped in a four-jar chuck in a TOS SN 71 B centre lathe as shown

Figure 3.19 while the opposite end is located in a three-point steady with roller bearings at the ends.

The sharp slicing tool is mounted at 15 degrees to the plane face of the module end and at an angle of about 10 degrees to the horizontal axis, as shown in Figure 3.18. Slicing was done at 40 rpm and a transverse feed of 0.8 mm per rpm. No cutting fluid was used. A swarf-free slicing with open capillary bores was achieved.

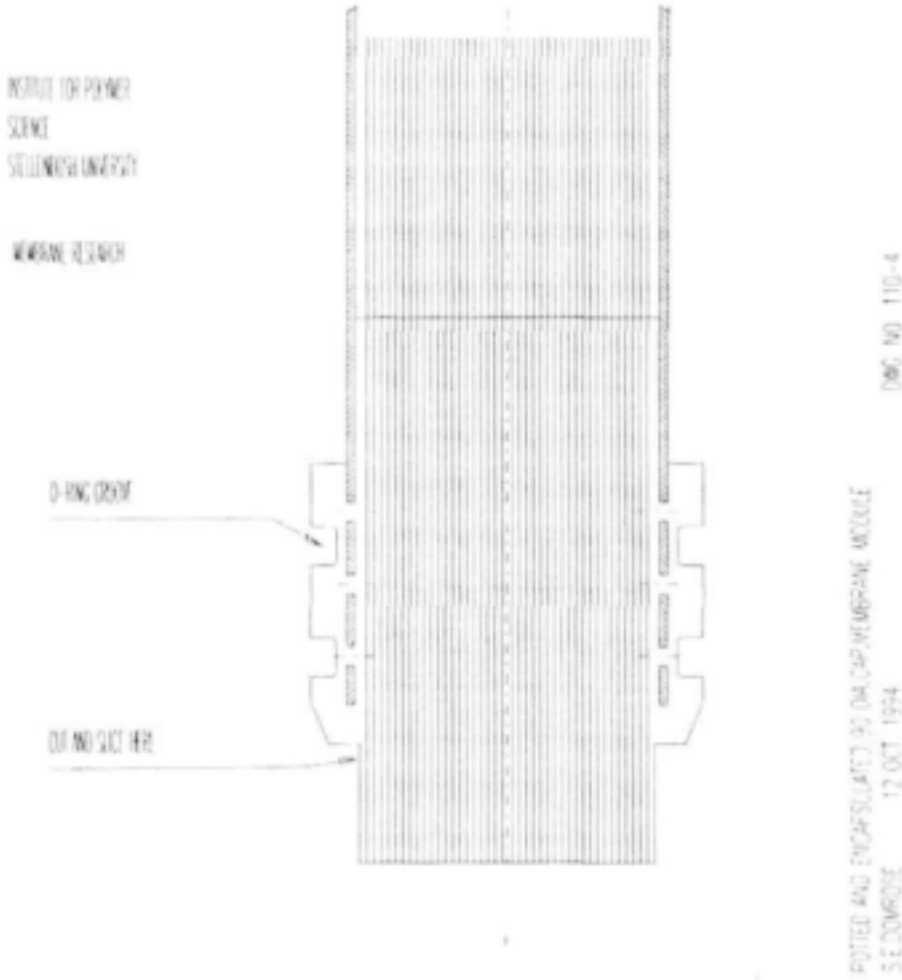


FIGURE 3.16: EPOXY ENCAPSULATED MODULE END .

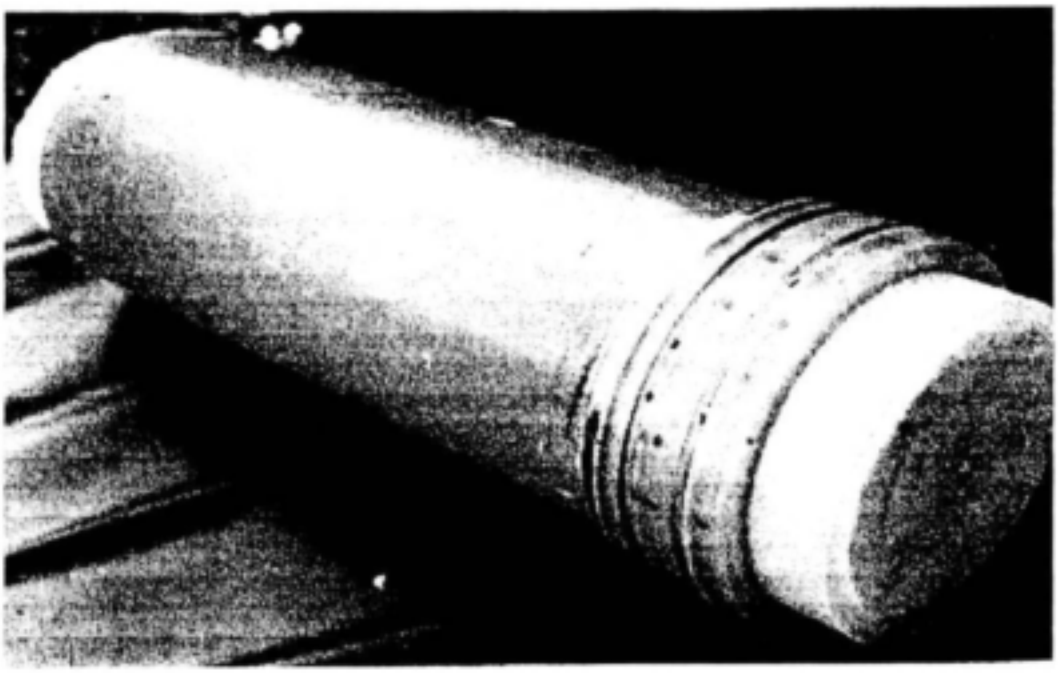


FIGURE 3.17: 200ØMM CAPILLARY MEMBRANE MODULE WITH ONE END ENCAPSULATED,SHOWING SST COMPRESSION BAND.

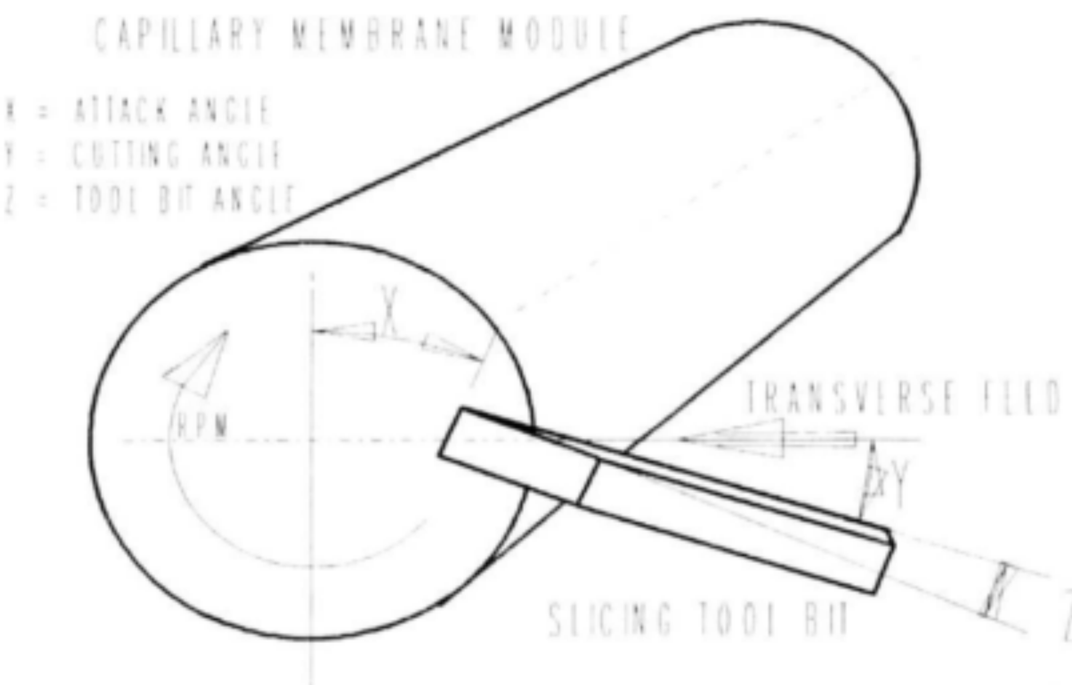


FIGURE 3.18: METHOD OF SLICING CAPILLARY MODULE ENDS .

Discs of 1 mm thickness were sliced off in one piece. Figures 3.20 and 3.21show the sliced ends. The flow channels for the epoxy during the centrifugal casting are clearly visible.

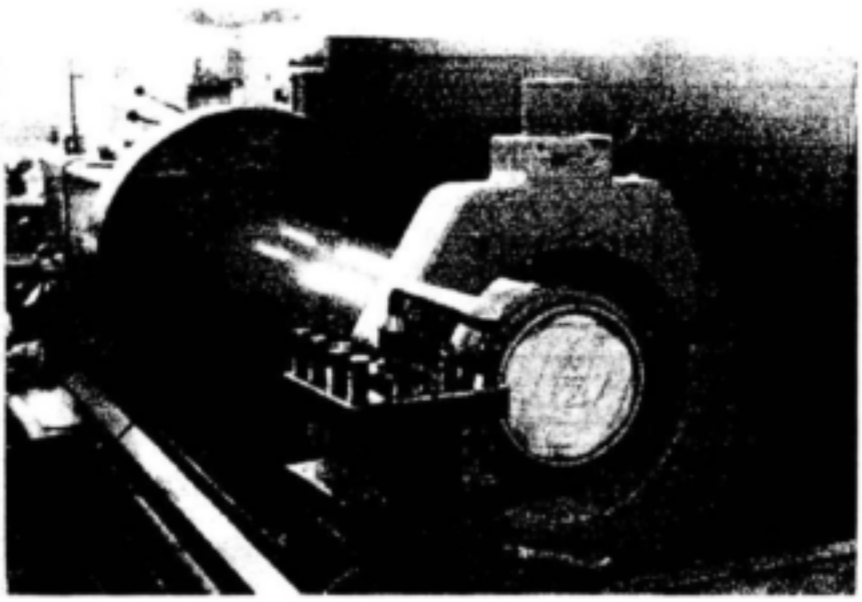


FIGURE 3.19: SLICING OF 200 MMØ MODULE.END IN A LATHE .

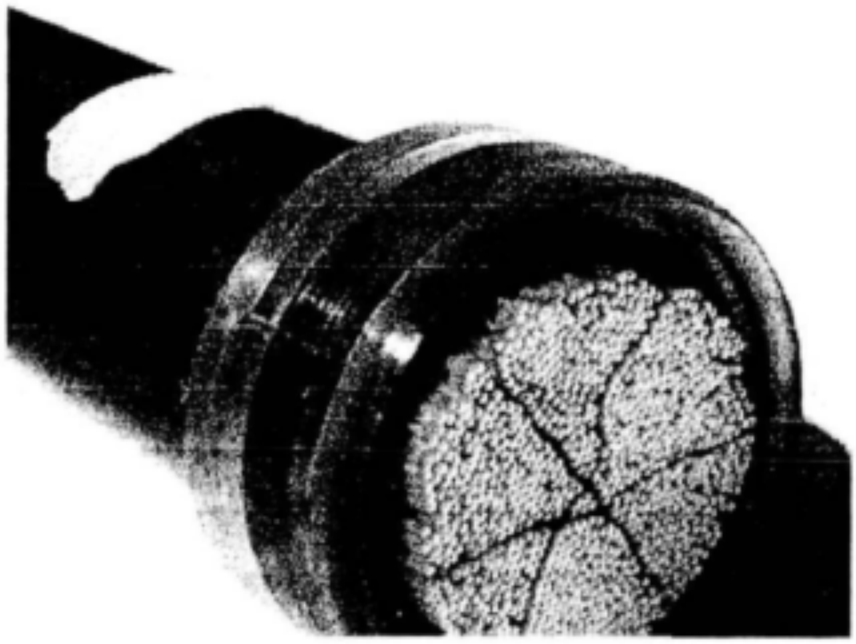


FIGURE 3.20: END VIEW OF A 90 MMØ SLICED CAPILLARY MEMBRANE MODULE

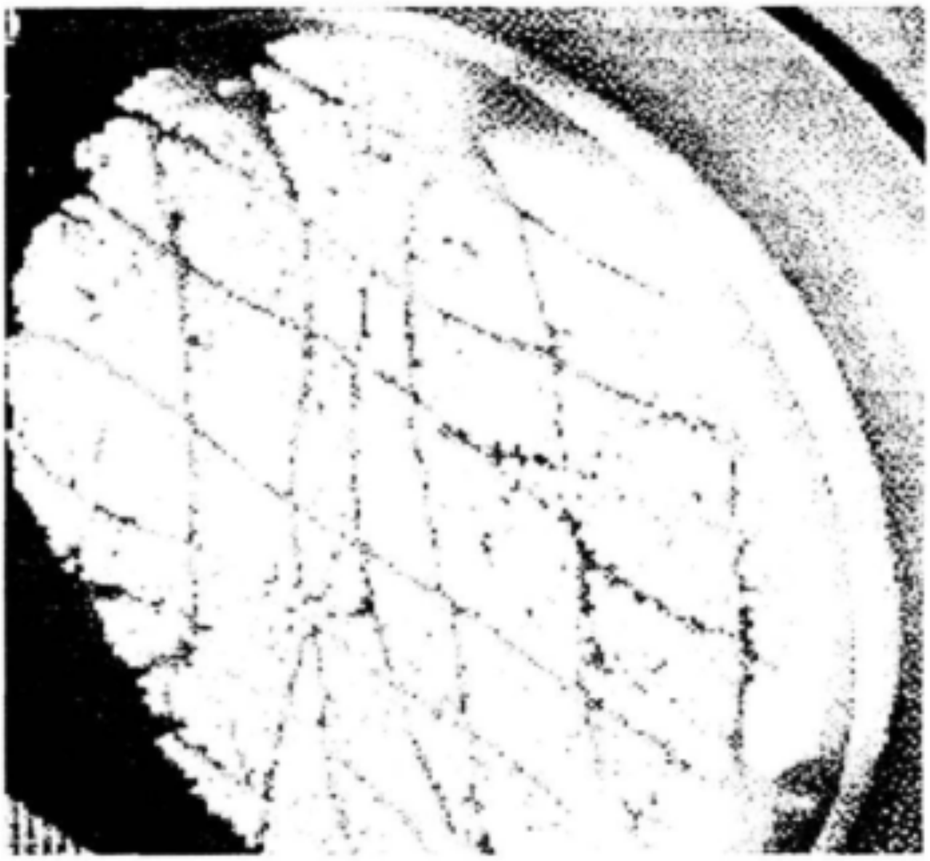


FIGURE 3.21 : CLOSE UP OF A SLICED END OF A MODULE. HEAD.

3.15 END CAPS

The end caps which were first used were fabricated by Membratek from uPVC, but leaked. Epoxy resin was used to seal this defect. Further leaks occurred at feed pressures above 60 kPa. Subsequent GRP covering and reinforcing did not stop the leaks which occurred again at about 80 kPa.

New stainless steel end caps were designed using standard components to reduce the cost from R 4300 for execution with dished ends to R2 900 per set. A full flange was reduced to only 4 fastening lugs to save on material, the dished end was made from a standard end cap and the feed inlet from a NW 50 hose connector.

An alternate design could be executed by using standard uPVC components from Astore Africa (Pty) Ltd., costing:

R170 for a 200 $^{\varnothing}$ mm end cap type CA1

R160 for a 225 $^{\varnothing}$ mm stub type QR1

R119.3 for a 225 $^{\varnothing}$ mm galvanised steel backing

R449.3 x2 =R898.6 +R8.15 for a hose connector plus R300.00 for machining of the tangential inlet and solvent assembly of the cap to the stub, at which point a

2 mm gap has to be built up with a PVC filler. Thus the total cost is R1206.75 This could be a potential point for leaking and tests would first have to be carried out to assess the gap-filling method. This will push up the cost close to the price of a SST set of end caps. SST end caps were chosen because of their strength, cost and reliability advantage, as well as the protection they offer to the module during transport and operation .
The only critical dimension is the inside diameter of the cap which fits over the module head. A plus tolerance has been specified to ensure that the cap can be assembled. Extra large cross section O-rings are fitted to compensate for ovality of the epoxy-encapsulated module head.

Figure 3.22 shows the SST end cap for the feed with an tangential inlet.

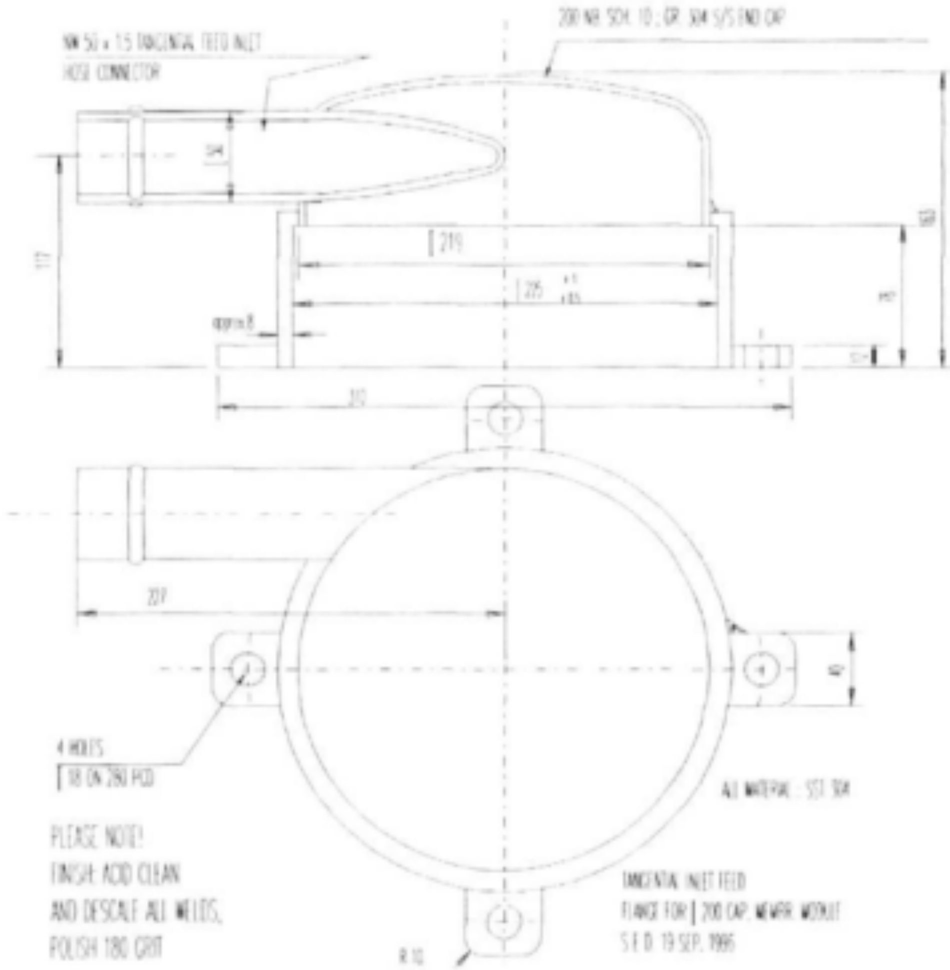
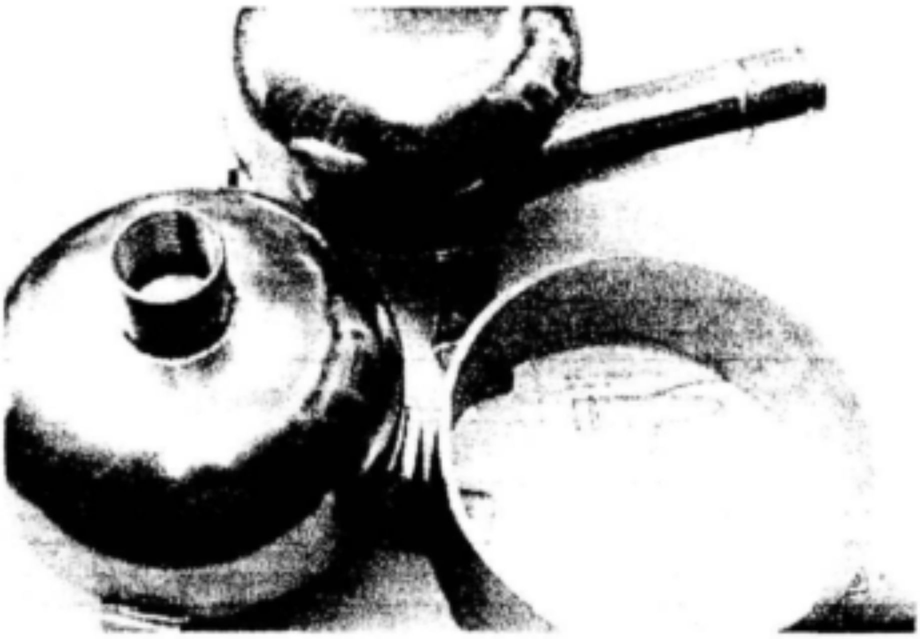


FIGURE 3.22: TANGENTIAL FEED INLET FLANGE.



F IGURE 3.23: END FLANGES DURING MANUFACTURE.

Figure 3.24 shows the SST outlet flange.

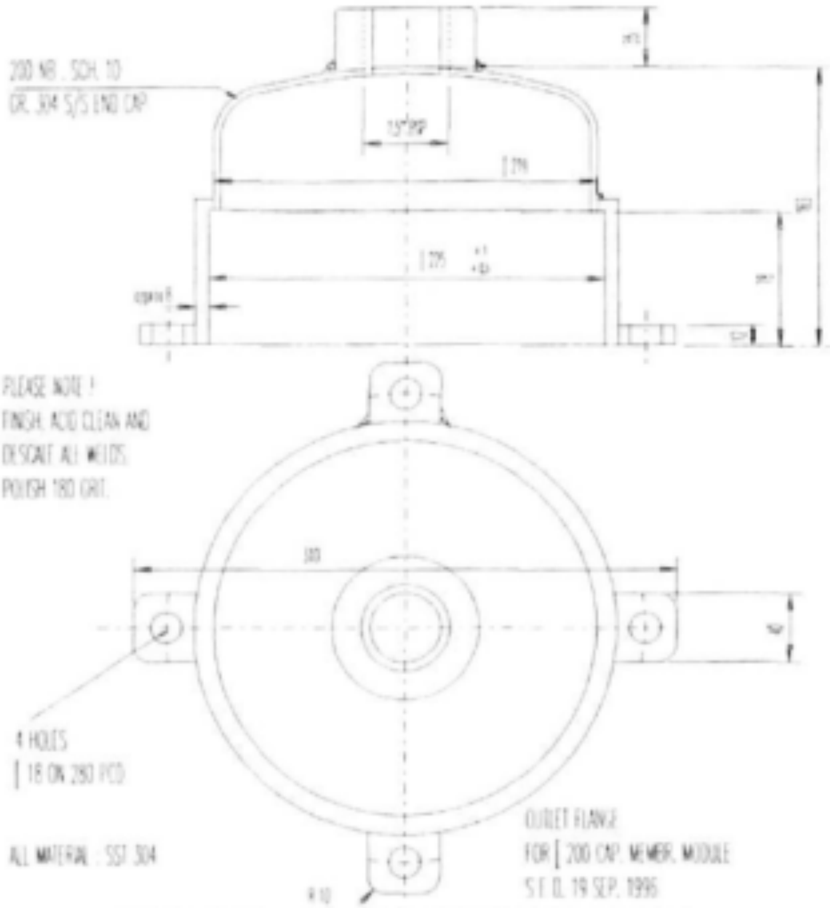


FIGURE 3.24.: OUTLET FLANGE

3.16 FINAL MODULE ASSEMBLY

Figure 3.27 shows the final module assembly with the tangential inlet flange, outlet flange and permeate outlet and tie rods fitted. Figures 3.25 and 3.26 show details of the tie rod and end flanges assembly, secured with SST hexagonal nuts.

3.17 TIE RODS.

Tie rods secure the end caps to the membrane module, which would otherwise be forced off the module by the feed pressure. Four tie rods keep the end caps in position. If the module shroud is made from stainless steel or filament glass reinforced plastic, then the end caps can be secured by a split collar and screws or bolts to the module where the epoxy encapsulation forms a shoulder. This shoulder prevents the collar from sliding over it, hence also the end cap, because this is connected to the collar. In cases where a PVC shroud is used, the multi-directional stresses might lead to an early failure, therefore tie rods must be used.

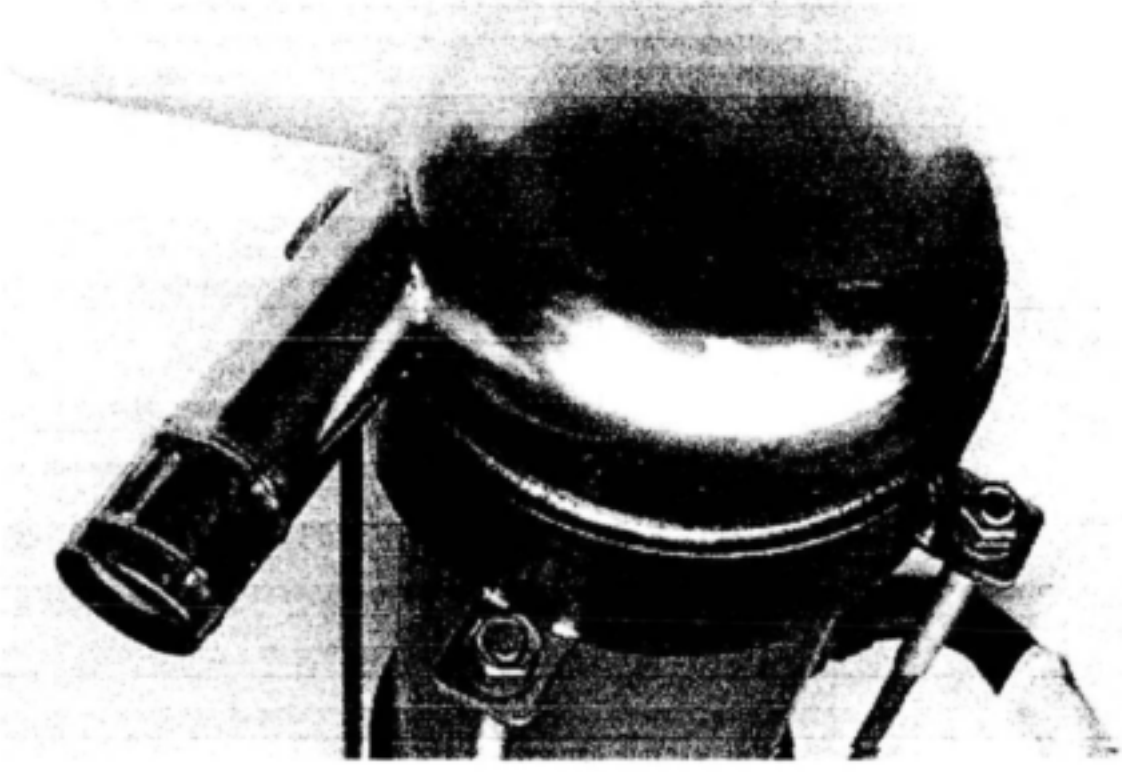


FIGURE 3.25 CLOSE-UP OF TANGENTIAL FEED INLET FLANGE END OF MODULE AND TIE-ROD CONNECTION.

FIGURE 3.26: CLOSE UP OF CONCENTRATE OUTLET END OF MODULE

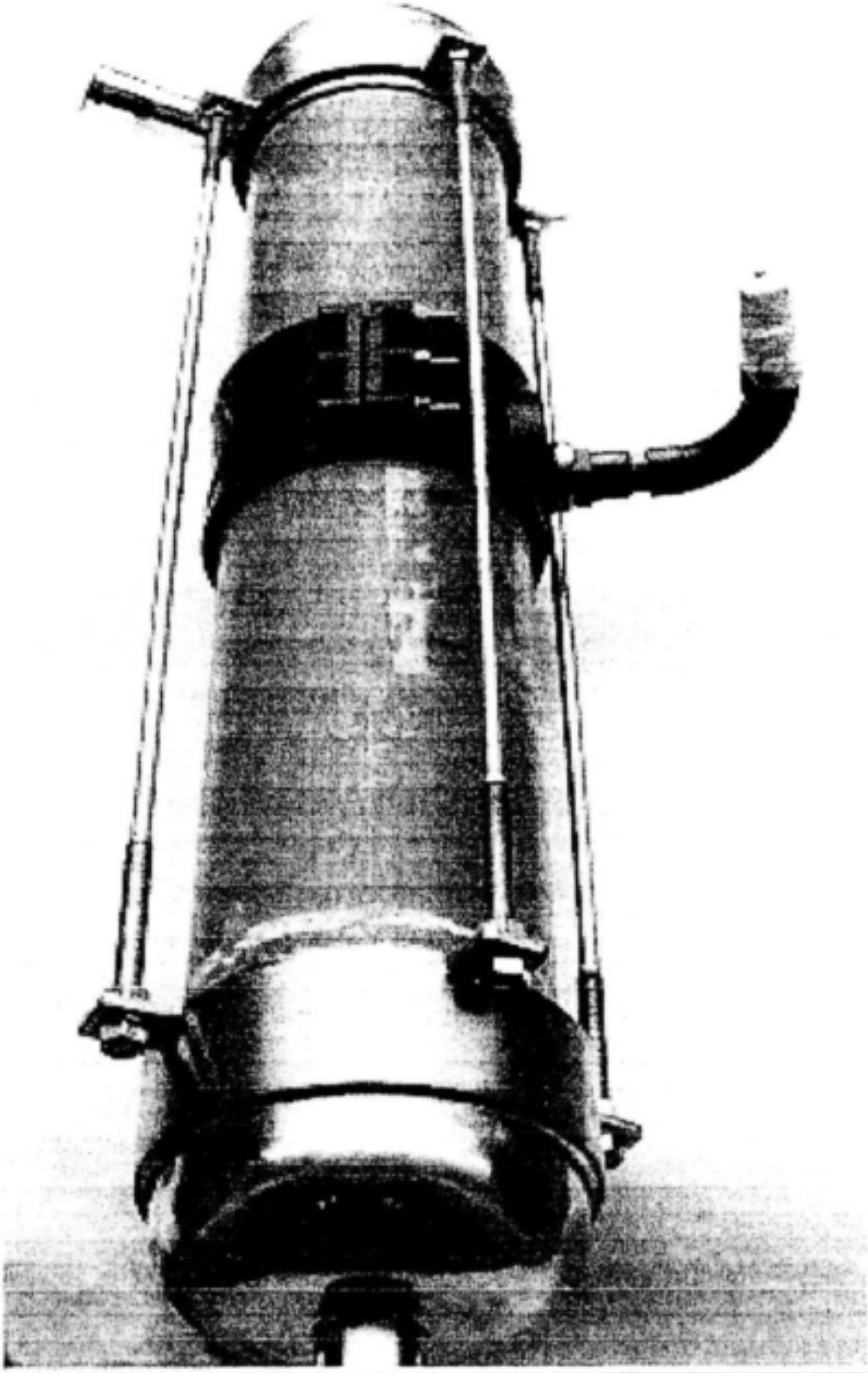


FIGURE 3.27:FINAL MODULE ASSEMBLY

3.18 CLAMP SADDLE FOR THE PERMEATE OUTLET

The clamp saddle is an off-the-shelf pipe fitting item, injection moulded from uPVC and competitively priced. The number of clamping bolts required varies according to the module size. A clamp saddle is attached to the module shroud to collect the permeate and lead it to the permeate tank. Again, this item is reusable and is easily removable from the module.

FIGURE 3.28_:SIEGFRIED DOMRöSE WITH A CAPILLARY MEMBRANE MODULE.

3.19 MANUFACTURING SPECIFICATIONS

MEMBRANES	UF Polysulphone capillaries 1.2-1.4mm bore x 1.8 mm$^{\varnothing}$
MMCO	approx. 50 000 dalton
PERFORMANCE	1ℓm^2/h at 20 °C
EFFECTIVE CAPILLARY LENGTH	960mm
N° OFF CAPILLARIES	4700
MEMBRANE AREA	18.4m^2
PACKING DENSITY	63.9%
WEIGHT (cartridge without fittings)	18.42kg
OVERALL module length	1175 mm
MAX.DIA.of head	225 mm
SHROUD (uPVC class 6 pipe)	200 mm$^{\varnothing}$

EPOXY encapsulation & potting: Membralock N°4 resin applied in a casting mould under centrifugal force.	Patent N° 477114
EPOXY MASS	6.5kg
MAX. OPERATING TEMP. for uPVC SHROUD	45 °C
MAX. FEED PRESSURE:	200kPa
MACHINING of module ends	Special slicing method.

CHAPTER 4
EVALUATION OF CAPILLARY-MEMBRANE MODULE PERFORMANCE

4.1 TEST FACILITIES

The existing test facility at Envig in Paarl, as shown in fig 4.1, was used. It comprises of a circulation pump with a bypass valve and a feed tank containing RO water. A pressure gauge was fitted to the capillary-membrane module inlet and outlet. The inlet flange had a tangential feed and there were 4 tie-rods securing the flanges. The pump volume was regulated by means of a bypass valve and the flow rate recorded on a flowmeter. Concentrate, bypass feed and permeate were circulated back to the feed tank. The backpressure was the height difference between the module permeate outlet and the top of the permeate pipe.

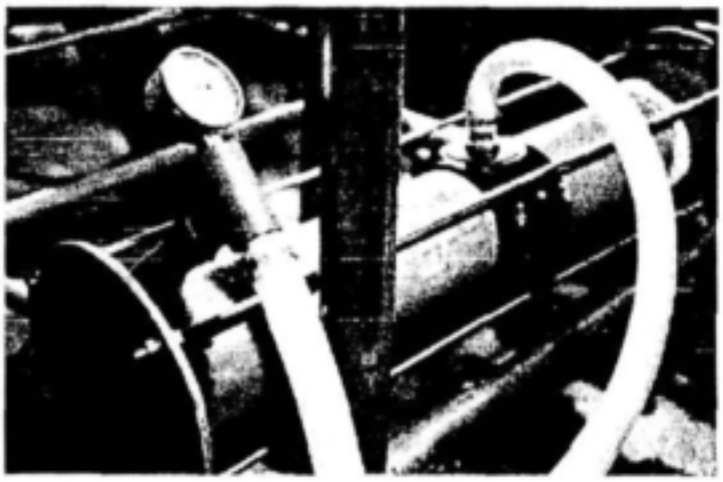


FIGURE 4.1: TEST FACILITY FOR TESTING OF 200°mm CAPILLARY MEMBRANE MODULE

One disadvantage of this arrangement was that there were no means of keeping the feed tank at a constant temperature. Due to the fact that the feed was not temperature controlled by means of a cooling coil, the test had to be interrupted as soon as the temperature reached 38 ^{0} C. The reason for this was that the module shroud could become distorted if the long-term temperature exceeded 45^{0}C. Because of the variation in temperature, some very interesting data was recorded, as is shown in Table 4.1. A process flow diagram for a test rig with a cooling coil regulating the feed temperature is shown in Figure 4.2

Feed Flow (m^3/h)	Inlet Pressure(kPa)	Outlet Pressure (kPa)	Temperature (°C)	Permeate flux (seconds/l)	Flux (l/min)	Flux $l/m^2.h$
6	50	30	25	12	5.00	16.29
7	50	25	29	7	8.57	27.92
6	50	30	25	11	5.45	17.77
8	50	30	38	9	6.66	21.72
5	50	30	25	10	6.00	19.54
8.5	70	30	28	6	10.00	32.57
9	70	30	30	5	12.00	39.09
9.5	70	30	32	4	15.00	48.86
10	100	50	26	4	15.00	48.86
15	120	70	26	3.5	17.14	55.84

TABLE 4.1: RO TEST RESULTS OF A 200Ø*mm* CAPILLARY MEMBRANE MODULE (MAY 1996)

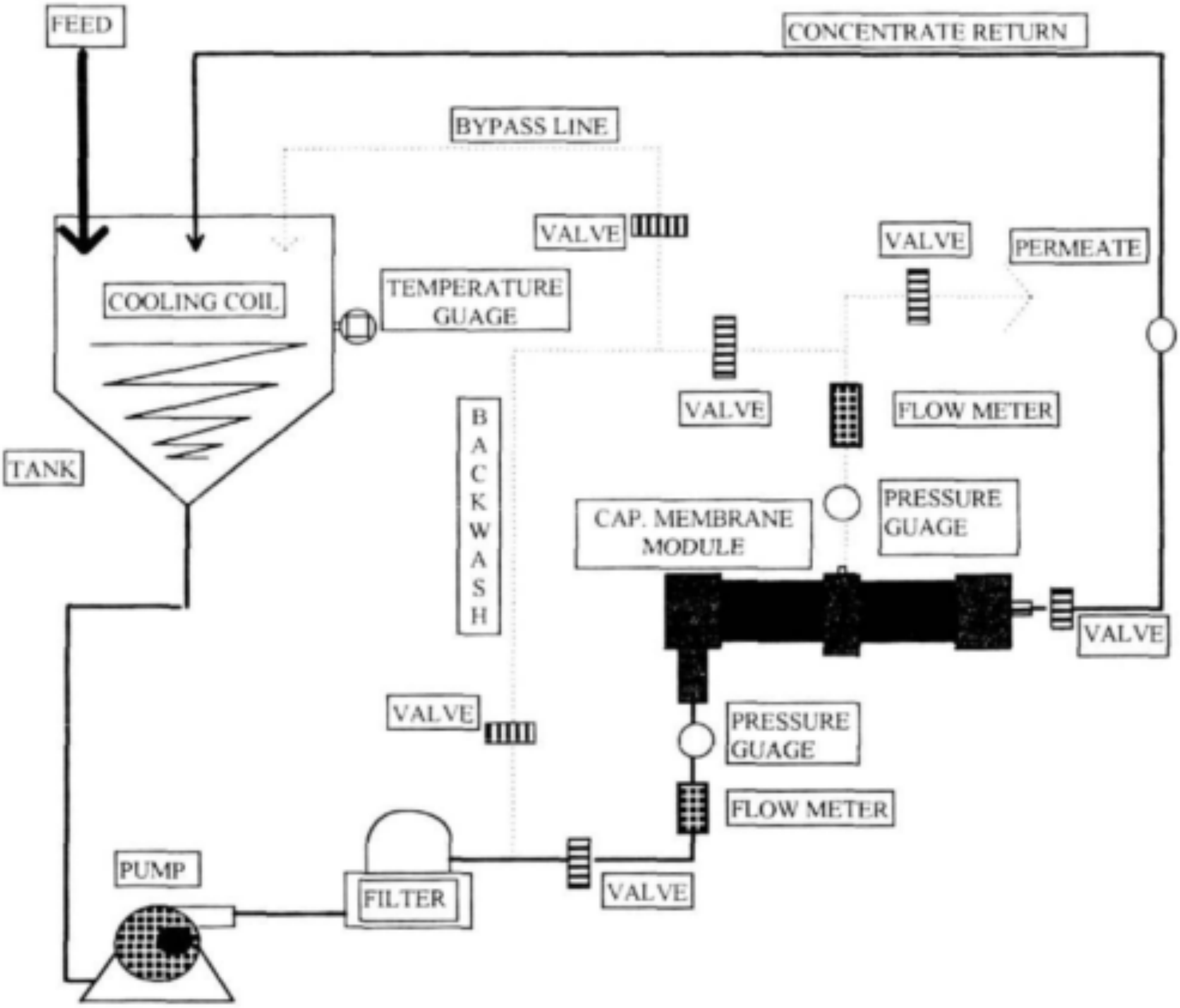


FIGURE 4.2: PROCESS FLOW DIAGRAM OF A TEST PLANT LAYOUT

4.2 MODULE INTEGRITY

Answers to several questions pertaining to module integrity were required, e.g: Will the epoxy encapsulation be strong enough or cave in or blow out under the feed pressure? Will all the capillaries be sealed? Will there be a hermetic seal between all the flow channels (i.e. feed, concentrate and permeate)? In order to answer these questions, the feed was coloured with Congo Red dye and pumped through the module. Any leak or imperfection in the module or the skinless capillary membranes would be visible as the permeate would then take on the colour of the feed. In the case tested, the feed was completely clear, indicating that the module was sealed in all the areas, namely the feed, concentrate and permeate. There were no leaks between the epoxy, shroud and clamp saddle. This further proved that all the capillaries where without pinholes or imperfections and that no damage to the capillaries occurred during the handling, assembly or epoxy encapsulation.

Results

A pure water permeate flux of 514ℓ/h at 0.3 m/s velocity and 22.5 kPa trans-membrane pressure at 28°C was achieved.

A pure water permeate flux of 1028ℓ/h at 0.66m/s velocity and a trans-membrane pressure of 50 kPa at 26°C was obtained.

Note:

The module had been tested with a Congo Red dye. No leakage of colour was detected and the permeate was colourless. This confirmed that the encapsulation and potting methods form independent hermetically-sealed flow channels and that no caving-in nor blow-out of the epoxy plug occurred.

Feed water temperature was not constant.

4.3 DISCUSSION

The results were very satisfactory. The value of the research to date has been confirmed by the success of a 90^{0}mm module which was field tested at Mon Villa. An important goal has been achieved with the development of the 200^{0}mm axial flow capillary membrane module. The test results obtained to date indicate that this module is suitable for industrial application. The module produces potable water at the lowest possible cost because of the large module membrane area. The use of such a module in a filtration plant means that the minimum number of components are required for the construction of such a plant, and operation and plant maintenance are minimal. The road is now open for the manufacture of even larger 100^{0}mm or350^{0}mm capillary membrane modules using the methods developed.

4.4 OPTIMUM PLANT OPERATING CONDITIONS

From the graph of Velocity of the feed vs Trans membrane pressure shown in Figure 4.3, a graphical representation of the tabulated data in table 4.1, drawn up to establish a window for the optimum operating conditions, it is seen that the optimum conditions are achieved when:

a) The plant is operated at a feed velocity of 0.42 m/s. This is because it is at this point in the graph that a plateau is reached for the flux, above which there is only a small increase in flux at the cost of a very sharp increase in pressure.
b) The trans-membrane pressure is set at 35 kPa

Below these values there is a considerable decline in performance, while above them the increase in performance is negligible and it is coupled with a sharp increase in energy consumption due to the higher feed pressure.

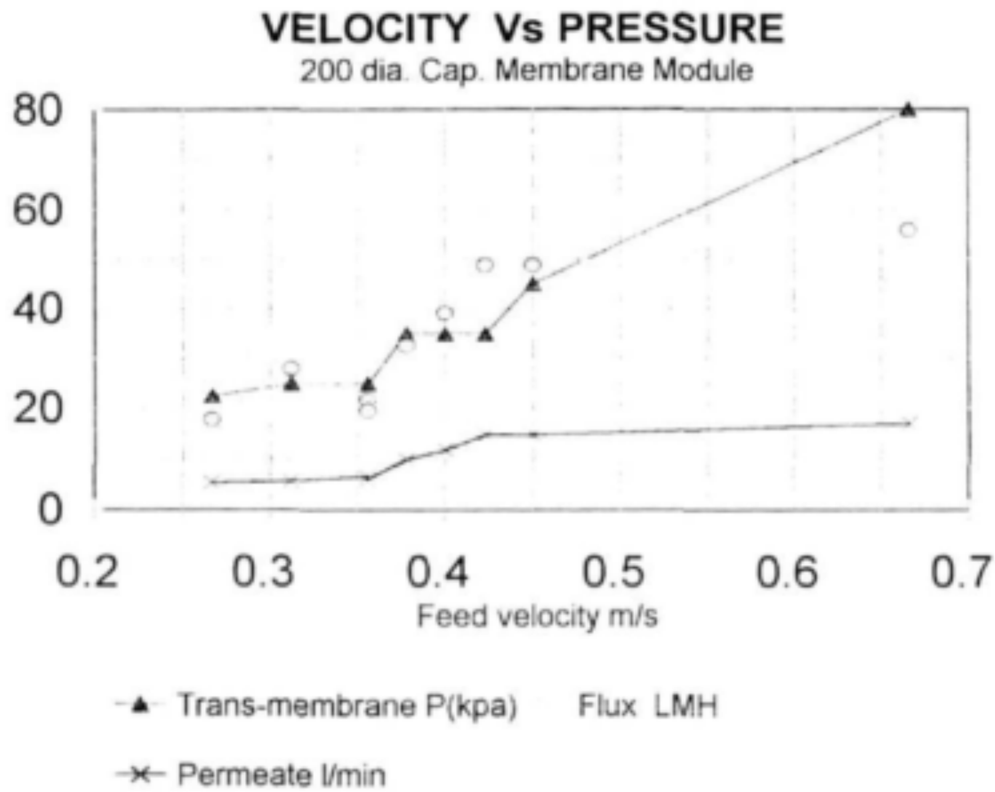


FIGURE 4.3: PERMEATE FLUX OF A 200mm DIA. MODULE AS A FUNCTION OF TRANS-MEMBRANE PRESSURE AND FEED VELOCITY

This optimum operating window must be individually established for each plant, because of pump performances, friction losses in the piping, valve configuration, filter and flowmeter arrangements. The benefits of these modules include operation of the plant in an energy-efficient mode, optimum performance and low stresses, all of which contribute to a longer capillary membrane module and plant life. Figure 4.4 shows graphically the influence of feed temperature on the permeate flux. At a feed temperature of 38°C the permeate is slightly higher than it is at the feed temperature of 25°C. The flux is 21.72 l/m^2.h as against 19.54 l/m^2.h, an increase of 11.15%.

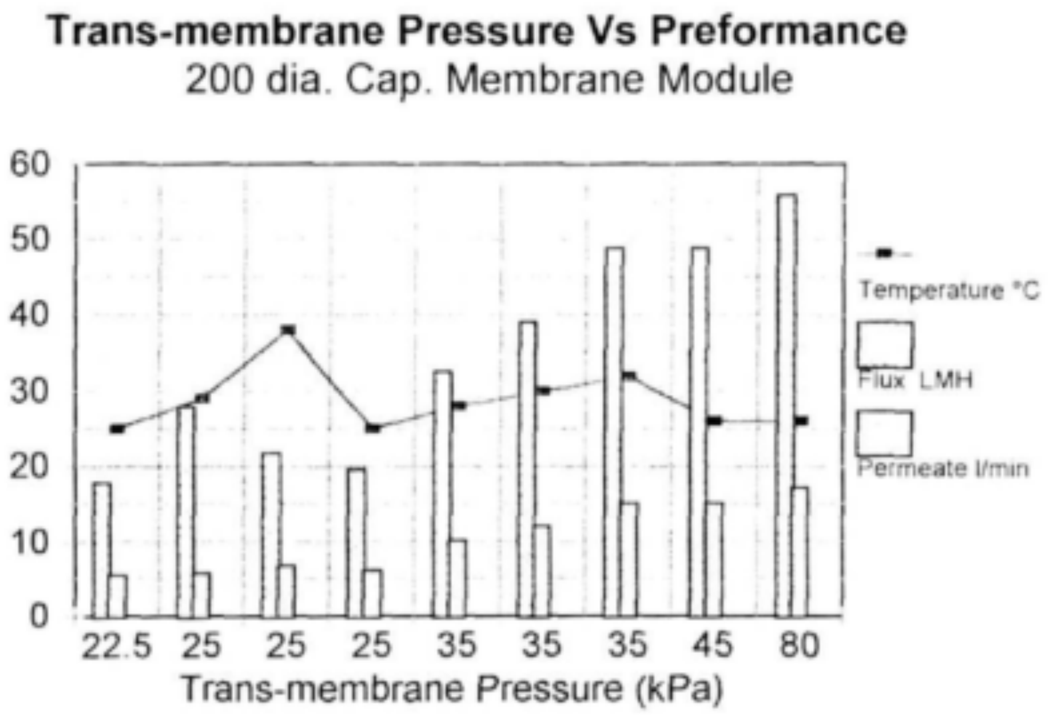


FIGURE 4.4:PROCESS VARIABLES vs PERFORMANCE OF A 200mm dia. CAPILLARY MEMBRANE MODULE

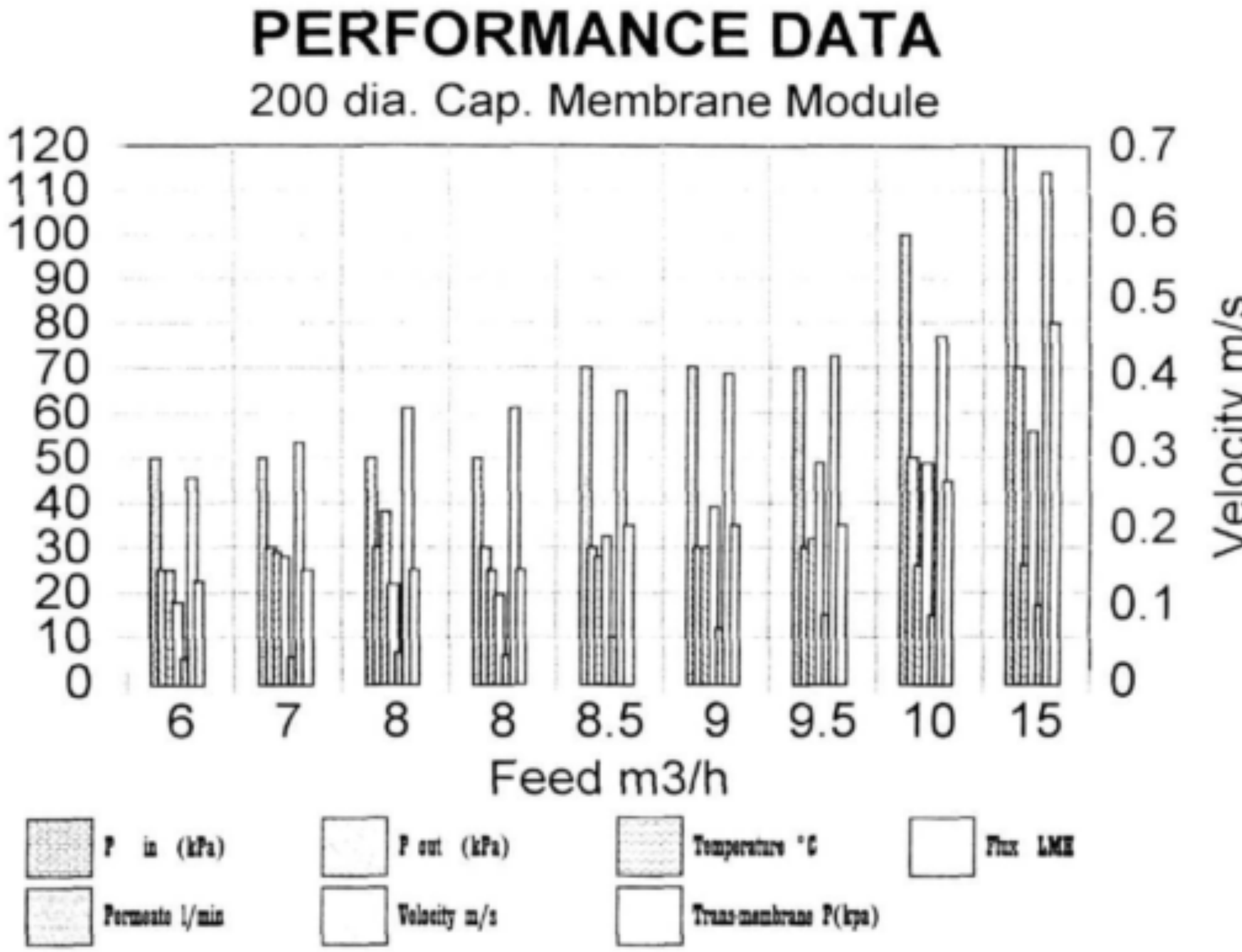


FIGURE 4.5: GRAPHICAL REPRESENTATION OF THE EFFECT OFF ALL PROCESS VARIABLES ON MODULE PREFORMANCE

In Figure 4.5 the data recorded during the bench test of the 200ᴓmm capillary membrane module provides a complete overview. It shows that with increasing feed volume and feed velocity the pressure drop in the module is also increased, from about 20 kPa (at a feed volume of 6 m^3/hr) to 50 kPa (at a feed volume of 10 m^3/hr).

CHAPTER 5
TRANSVERSE-FLOW CAPILLARY-MEMBRANE MODULE

5.1 AIM OF MODULE DEVELOPMENT

The aim of this aspect of the project was to develop a transverse-flow capillary membrane module with ten or more capillaries, as shown in Figure 5.1.

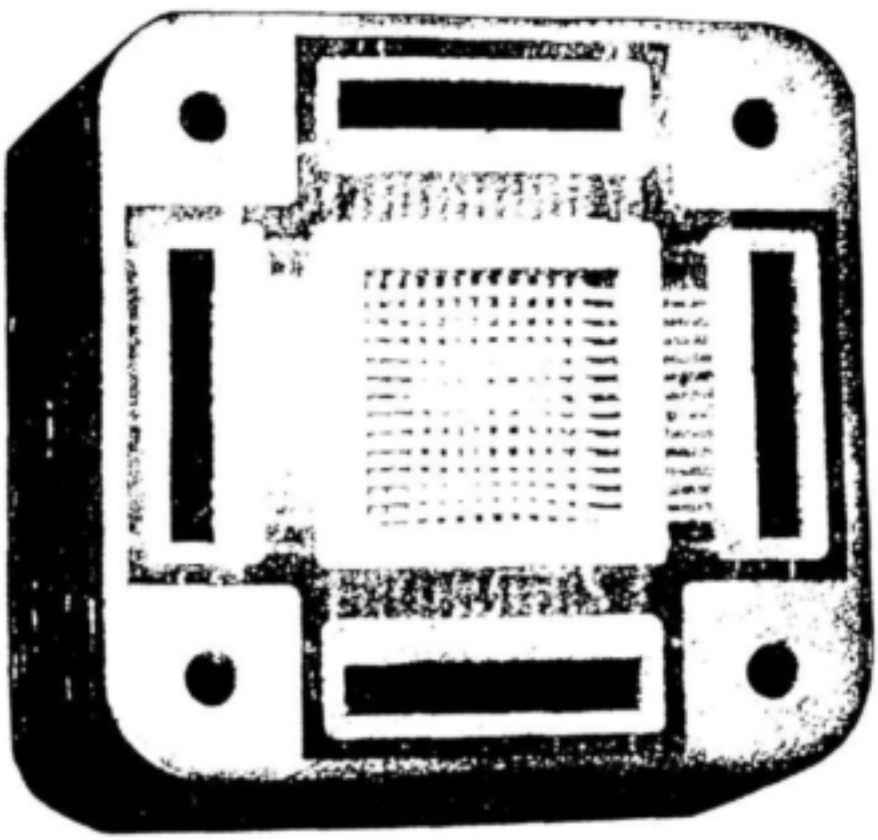


FIGURE 5.1: 13 TRANSVERSE-FLOW CAPILLARY-MEMBRANE MODULE

Stacks of modules of various heights were assembled by means of inserting capillaries in the locating grooves, clamping ten or more spacers together and sealing the five flow-channels from each other by casting epoxy resin into the spaces provided. Such modules are useful in many applications, eg in laboratories to oxygen-enrich mineral ore slurries and as bioreactors (at Rhodes University in Grahamstown) to grow enzymes under controlled conditions. A transverse-flow capillary membrane module is much more versatile than an axial-flow capillary membrane module. The axial-flow capillary membrane module is capable of handling only one feedstream which can be either gas or liquid, and has two separate channels. The transverse flow module has five separate channels and can process two different feedstreams, which may be either both liquid, both gas, or one liquid and one gas.

5.2 DESIGN OF A SCALED-UP SPACER

The module with 13 capillaries shown in Figure 5.1was a success as is was functional and operational. It also gave an idea of which materials would work and which would not; but increasing the size of the spacer was not only a matter of scaling up the existing one (which was originally developed to hold ten to thirteen capillary-membranes in a module spacer). Several factors had to be considered, such as the breaking strength of the capillaries, the maximum unsupported distance, support ribs, epoxy casting and potting, as well as assembly techniques. The selection of a suitable spacer material was important; it had to bond with epoxy, be strong and rigid, suitable for injection moulding, flow readily to fill the small sections in the mould and have good chemical resistance.

Various design concepts were considered such as the building up of the spacer from four sections, making it only half the depth, and using soft-sealing section inserts. In addition, we wanted to injection-mould the spacer oursleves on our Buhler Miag injection-moulding machine. We could therefore not exceed the maximum shotweight, locking force and cavity pressure of the machine. Indexing of the spacer, including stacking variations, were to be retained. Figure 5.2 is a drawing of an up-scaled version of a spacer, which holds 68 capillaries. It has a lattice to support the capillaries in-between the epoxy-anchored ends. The stress-strain diagram of a typical capillary membrane (No 60) given in Figure 5.3 shows that all stresses must be well within the proportionality limit, including estimated further reductions for long-term creep and a reasonable safety factor. For this reason the lattice grid was incorporated in the spacer design. An important equation derived from this diagram is:

Modulus of elasticity: $E = \frac{\sigma}{\varepsilon}$

where : σ = tensile stress ε = elongation

This equations is needed to calculate the capillary burst strength and collapse pressures as well as the tensile strength and the capillary-design strength. These values must be established for each type of capillary, because reference tables give data only for solid. materials and not for porous materials such as capillary membranes.

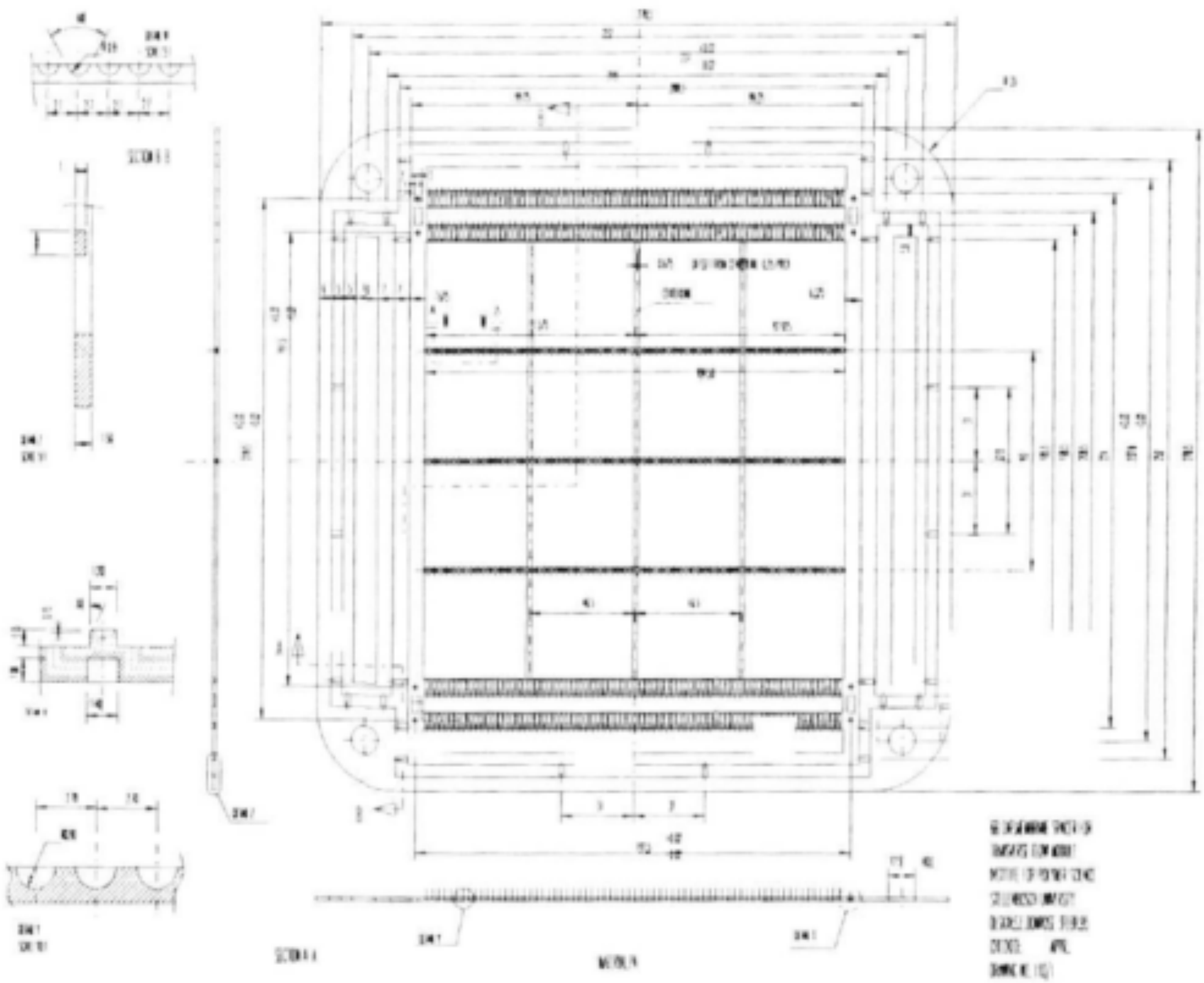


FIGURE 5.2: TRANSVERSE FLOW CAPILLARY MEMBRANE SPACER LOCATING 68 CAPILLARIES. (CAPILLARY-SUPPORTING LATTICE SHOWN IN THE PRODUCT DRAWING)

The full depth of the locating grooves has been maintained (although a half round groove would give a better seal), as otherwise no epoxy would wet the capillaries in the membrane separating space because the filling of the mould would be even more difficult. This in turn would mean that the strength and rigidity would be reduced and there would be an extra joint and a potential leak site.

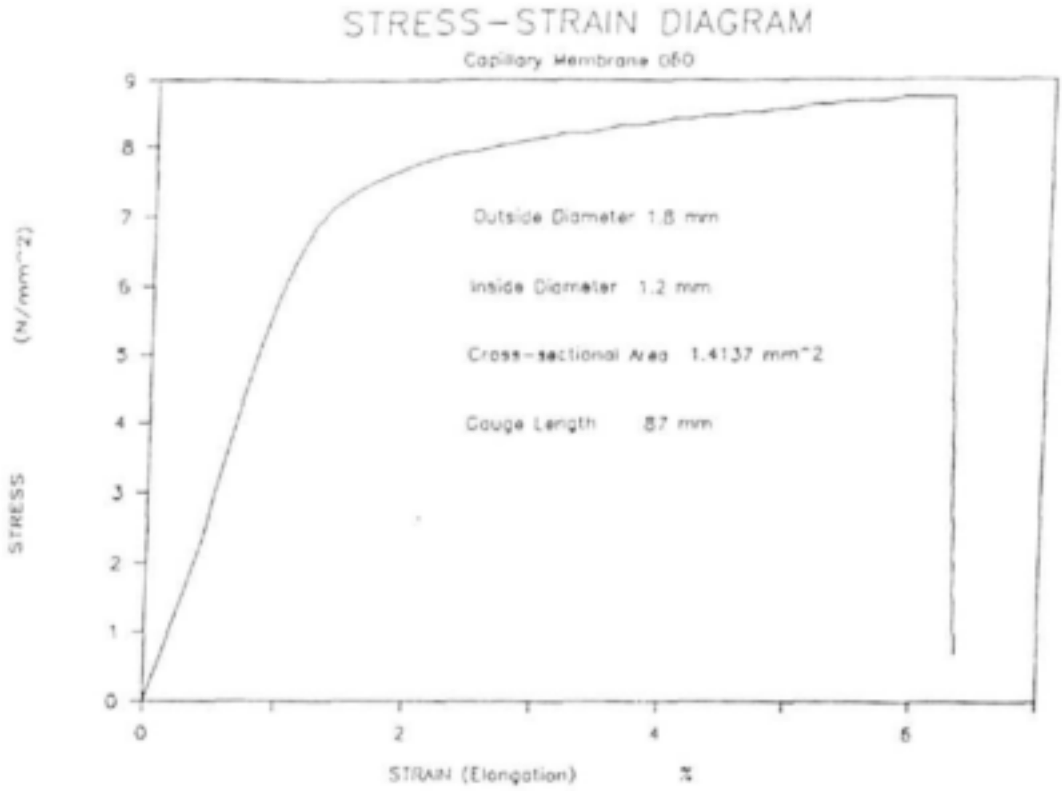


FIGURE 5.3: STRESS-STRAIN PROPERTIES OF A CAPILLARY MEMBRANE

5.3 SPACER MANUFACTURING METHOD

Injection moulding is a accurate way of manufacturing without the need for any subsequent finishing. Parts are produced in a very short time.; In this instance it would take about 25 seconds to produce a moulding. A disadvantage, however, is that the injection mould would cost approximately R106,000, made up as follows:

Prepare NC programs	R	13 200.00
Machining and assembly	R	23 240.00
Consumable material and tooling	R	1560.00
Die set from DME Hestico in C.T.	R	13 000.00
Hotrunner nozzles 5 off	R	25 000.00
Temperature control box	R	15 000.00
Mould design	R	15 000.00
Total cost	R	106 000.00

If this method were to be used, it would be advisable to first make a mould filling simulation study because the spacer is a very complicated part to fill on account of the long flowpath, the thin wall section and the small gates connecting one part to the next.

5.4 C-MOULD ANALYSIS

C-Mould is a computer program which simulates the dynamic injection mould-filling process with a polymer melt. It gives information on the position of the gates, injection profile, maximum pressure, weld lines, venting positions, temperature distribution, frozen layers fraction, etc. This work could be carried out at the University of Cape Town's Finite Element Analysis Service Section, and would cost R2850.00

5.5 LASER CUTTING OF A MEMBRANE SPACER

Eiger Engineering in Alrode SA could cut a polymer spacer from nylon or polyester sheet, but could not do the halfround membrane-locating grooves. The grooves would have to be machined, but this might distort or even damage the part.

Schuurman Engineering in Cape Town, with whom we are in contact, are setting up and commissioning a Trumpf CNC Traumatic TLF 2600 laser cutting centre with 180 to 2600 Watt output. It would not be possible to laser cut PVC as corrosive vapours would be formed during cutting and these would clog up the lenses of the laser cutter. Spacers cut from Nylon 6 sheet 3 mm thick would cost:

Laser cutting per spacer (min of 20)	R131.67
Material per spacer	R30.00
Machining of locating grooves	R40.00
Total cost per spacer	**R201.67**

A module of 20 spacers high would therefore cost R4033.40 for spacers alone. A locating jig for the machining of the grooves at a cost of R600.00, as well as a further R800.00 for a profile cutter, must also be allowed for.

5.6 OTHER PROTOTYPING METHODS

A full-scale transverse-flow capillary membrane module cannot be constructed without incurring the high cost of an injection mould until the concept of a scaled-up model is proved. The following methods of manufacture can be used, because new technologies have become locally available in Cape Town:

a) **Stereo Lithography** builds up a model in a tank from a polymer in layers which are UV-cured. A CAD drawing is required. This is used to make a 3D solid computer model and from this the actual model is generated. A drawback is that the model would be too brittle.

b) **Laminated Object Manufacture** is similar, but uses a material in sheet form, which is fed from a roll over the laser workstation. The choice of materials is wide, though in most instances paper is used. This gives a very strong model and is suitable for the membrane spacer.

5.7 PROTOTYPE MOULD

As a number of spacers are required to build a working model of a transverse flow capillary membrane module it is better to use this route, which entails the following:

Make a negative spacer (a mould) from HDPE. Fit a top plate, which is clamped to the other half. Further, provide a funnel to pour in the epoxy and also a riser for venting of any air trapped in the mould.

In this way, one spacer could be cast per day. This would take much longer than injection moulding, but is much cheaper and can be used until the larger scaled-up module has been evaluated, tested, modified and proved.
According to the latest information, the cost of a prototype mould for gravity casting of spacers in epoxy would be as follows:

Supply a 2D CAD drawing, from which a stereo-lithographic computer model is made.

From this computer model a solid computer model may be made		R1800.00
From this a laminated cavity mould is made.		R2800.00
		R4600.00
	VAT	R 644.00
	TOTAL COST	**R5244.00**

The laminating can only be done in paper, because of bonding problems encountered with HDPE. A release coat must therefore be applied to prevent the epoxy from sticking to the mould.

5.8 ROBOTICS SUB-ASSEMBLY

With larger transverse-flow capillary membrane modules, the manual placing of the capillaries into the locating grooves would be too time consuming. A more automated method such as one using a robot to insert the capillaries and trim them to length should be considered.

5.9 MATERIAL SELECTION FOR THE TEMPLATE

If the membrane spacer is produced by the injection-moulding process, Polyamid (PA), (a nylon) could be used. PA has good chemical resistance, bonds reasonably well with epoxy and flows easily to fill a mould with a complicated shape. High-impact Polystyrene (HIPS) was the only material used to fill the mould for the spacer with 10 capillaries. Sticking of the part in the mould cavity was a problem, and a silicone release agent had to be used. Polypropylene gave parts with lots of flash (unwanted material on the outsides of the moulding). PA could not be used successfully because the prototype mould had no heating channels.

Polymer without memory in sheet form was considered, from which a template is cut out and the locating grooves for the capillaries pressed in. Because, in this instance, the polymer has no memory, the locating grooves will keep their pressed in shape and not partially return to their original shape, as in the case of a polymer with memory. Disadvantages include:

- the lack of precise control in any later mass production,
- the long process of first formulating the memory-less cold forming polymer
- flat sheet extrusion and conversion

These factors are not favourable for a high quality and repeatable process.

5.10 PROTOTYPE OF TEMPLATE CONSTRUCTED FROM COREX SHEETING

A scaled-up prototype with 59 capillaries, as shown in Figure 5.4 was constructed from Corex Sheet, which is extruded from polyethylene in a box profile. The sheet is 3mm thick and has a top and bottom skin of about 0.2mm and ribs perpendicular to it, measuring 0.15mm thick at 3mm pitch. Viewed from the end of the sheet, the rectangular tubes of 2.6 x 2.7mm in the sheet are visible. The 2mm$^{\varnothing}$ capillary membranes are inserted into these. For the prototype the template was manually cut out in sections by hand, and then assembled with adhesive tape. A Clicker die, constructed from a band-knife, where the knife is formed in such a way as to suit the shape of the spacer, is mounted in a hard-wood laminated block. The template is cut out in one operation from Corex sheeting. A clicking die, as used by carton makers, will cost about R500.00.

A further idea was to insert the capillaries into the template, casting epoxy into the sealing channels of each template separately and then to assemble a stack which is finally epoxy-cast into a module block in a mould, forming all subsequent channels and clamping holes.

Even when epoxy is cast into an individual template (to keep the hydrostatic pressure low), epoxy leaks and runs past the gap formed by inserting a round capillary into a rectangular channel. This makes it impossible to produce prototypes without the high tooling cost of an injection mould. An exception might be a Corex-type profile with round channels into which the capillaries fit with minimum play, if such can be obtained.

The possible alternatives to an injection moulded template could be the following:

- Use paraffin wax to seal off all gaps between the capillaries and the Corex sheet, then cast the epoxy. The wax is later melted out in warm water at 70°C.
- Produce a silicon rubber mould which aligns the capillaries, and cast an epoxy frame around the capillaries to form a template. Stack the templates, 20 layers or more high, in a mould and cast a module block.
- Punch out a template from a solid PVC sheet. Drill holes to locate the capillaries.
- Arrange capillaries in a silicon rubber mould and cast a template in paraffin wax. Assemble templates in a stack and cast in epoxy resin.

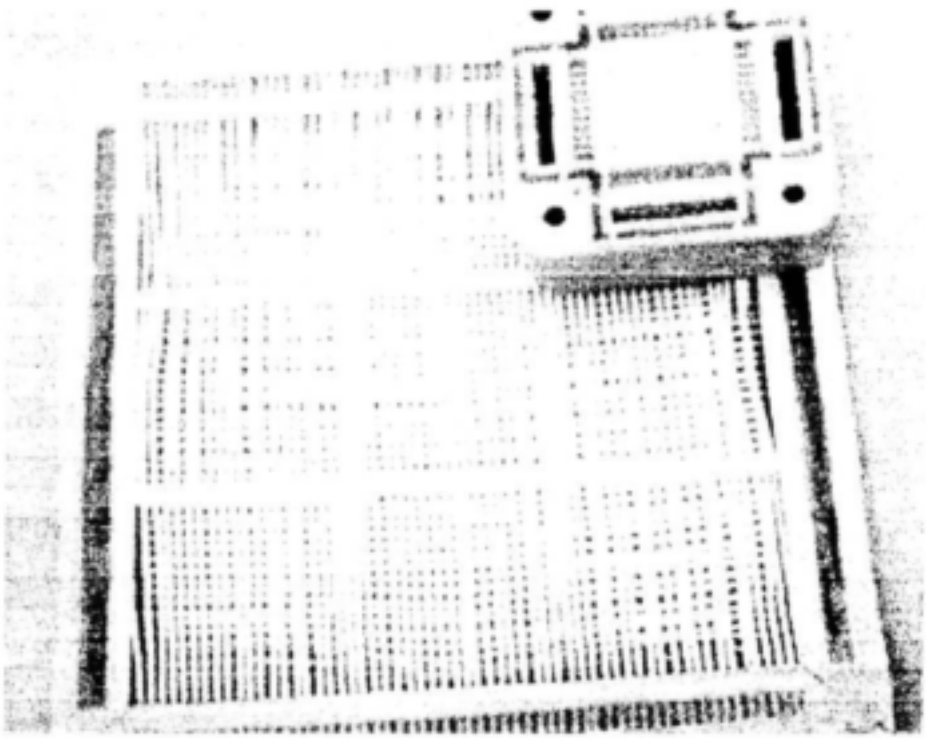


FIGURE 5.4: PROTOTYPE OF A 68 CAPILLARY MEMBRANE TRANSVERSE FLOW SPACER. (existing module in top right hand corner illustrates increase in size)

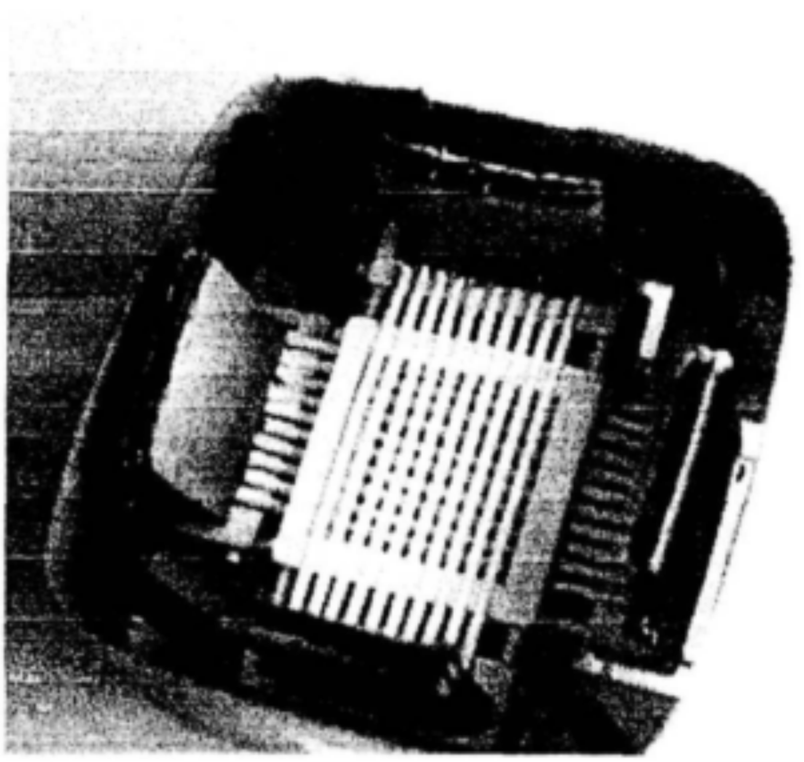


FIGURE 5.5: MOCK UP, ILLUSTRATING THE CONCEPT OF SCALING UP OF THE TRANSVERSE FLOW CAPILLARY MEMBRANE MODULE

5.11 ADVANCED PROTOTYPE MOCK UP OF TRANSVERSE FLOW MODULE

Figure 5.5 illustrates the concept of an advanced method for the production of transverse flow capillary membrane modules based on the existing modified 10 capillary template.

Advantages of this advanced prototype mock-up include:

- Only an inner injection-moulded template with locating holes instead of grooves is used. This reduces the size and complexity of the template and the tool cost.
- Holes in the template to locate the capillaries eliminate the leaking of epoxy onto the capillaries in the feedstream zone. Leakage reduces the effective membrane area and also creates a potential failure area.
- The four flow channels are formed during the assembly of the module in a mould and epoxy casting.
- Clamping holes are formed during the assembly of the module in a mould and epoxy casting.
- The outer periphery of the module is formed during the assembly of the module in a mould and epoxy casting, ensuring a hermetic seal and encapsulation.
-

This method ensures a reliable, reproducible and high quality module. The injection moulded template size is reduced and there is no need to rely on the dubious bonding of the polymer and epoxy to form a seal. In all critical sealing areas the epoxy-to-epoxy seals are cast in one operation.

5.12 WHY USE THE *SOLID WORKS* DESIGN PROGRAM?

Solid works is a solid-modelling design program which is more advanced than wire frame programs. It enables the construction of parts and assemblies on a computer screen. The design is three dimensional, and can be viewed from different angles and sides. Changes in design can be made in a component or assembly drawing and interfaces and movements can be checked. Mistakes can therefore be corrected at the design stage instead of after manufacture, eliminating expensive and time-consuming alterations.

People from diverse disciplines can participate at the design stage because the necessity of both reading a two-dimensional drawing, which even some engineers find difficult, and of mentally converting that two dimensional drawing into a three dimensional object, which could be positive or negative, depending on whether it is a mould or a product, is eliminated. At present, only fully trained engineers in practice can perform these mental acrobatics. Solid Works relieves engineers of some of the strain of visualising complex objects and enables more effort to be applied to creative design. Communication and participation are possible right from the start, removing the loneliness and isolation of the designer and promoting team work.

Mistakes and shortcomings are eliminated at an early stage and multi-disciplinary participation and input are possible.

As is to be expected, this technology comes at a price, not only in terms of money (we obtained the program at 10% of the normal cost as an educational program), but also in terms of time and computer hardware as the operating system had to be upgraded from a 16 to 32 bit, and RAM from 8 to 16 and finally memory to 74 megabyte to provide for the higher demands of the video display graphics in the program.

5.12 *SOLID WORKS* DESIGN OF SCALED-UP TRANSVERSE FLOW CAPILLARY MEMBRANE MODULE.

This module was to be designed with an increased size, to locate about 68 capillary membranes. The new design was to have **locating holes** instead of locating grooves and **support ribs or lattice** to reduce the unsupported span of the capillaries to about 35 mm.

Only the **inner frame** will be injection moulded and the other parts of the module will be **cast in epoxy resin**. The casting mould will form the **four flow channels** and the **four clamping holes** and the **outer epoxy encapsulation** to ensure a **reliable, repeatable and hermetic seal** in the block type module and or the modular type.

5.13 DESIGN CONCEPT ANALYSES

For this purpose the various design and development stages will be classified as:

- 1st Generation: The transverse flow module with 10-13 capillaries, or resent module See Figures 5.1and 5.4.
- 2nd Generation: The transverse flow module with 68 capillaries is a scale-up of the 1st Generation module, but with a support lattice.
  See Figures 5.2, and 5.6 - 5.10.
- 3rd Generation: The transverse flow module with 68 capillaries and support lattice has only an inner injection moulded spacer, reduced in size, with locating holes instead of grooves. With the new epoxy casting concept the mould forms the outer module configuration, four flow channels and the four clamping holes ensuring a hermetic epoxy encapsulation.
  See Figures 5.4 - 5.5 and 5.11 - 5.16

The 1st generation transverse flow module proved itself useful as a laboratory bio-reactor.

The 2nd generation transverse flow module with 68 capillaries and lattice support is a design study and served its purpose well as a stepping stone to the design and development of the 3rd generation module.

The 3rd generation transverse flow module is advantageous for the following reasons:

- Consistent and high quality mass production.
- Potential commercial application because of its larger size.
- Reduction of injection mould cost, because only an inner spacer template is required.
- Leaking of epoxy onto the capillaries in the feed channel during assembly is eliminated by having locating holes instead of grooves.
- Hermetic seal of the module due to the complete epoxy-encapsulation.
- Lattice provides orderly and firm location, as well as support, of the capillaries.
- Huge development costs have been saved by the design study which, in bypassing the actual manufacture of the 2nd generation, enabled focus to be directed to the 3rd generation transverse flow capillary membrane module.

SCALE UP OF PRESENT SPACER CONCEPT WITH SUPPORT LATTICE

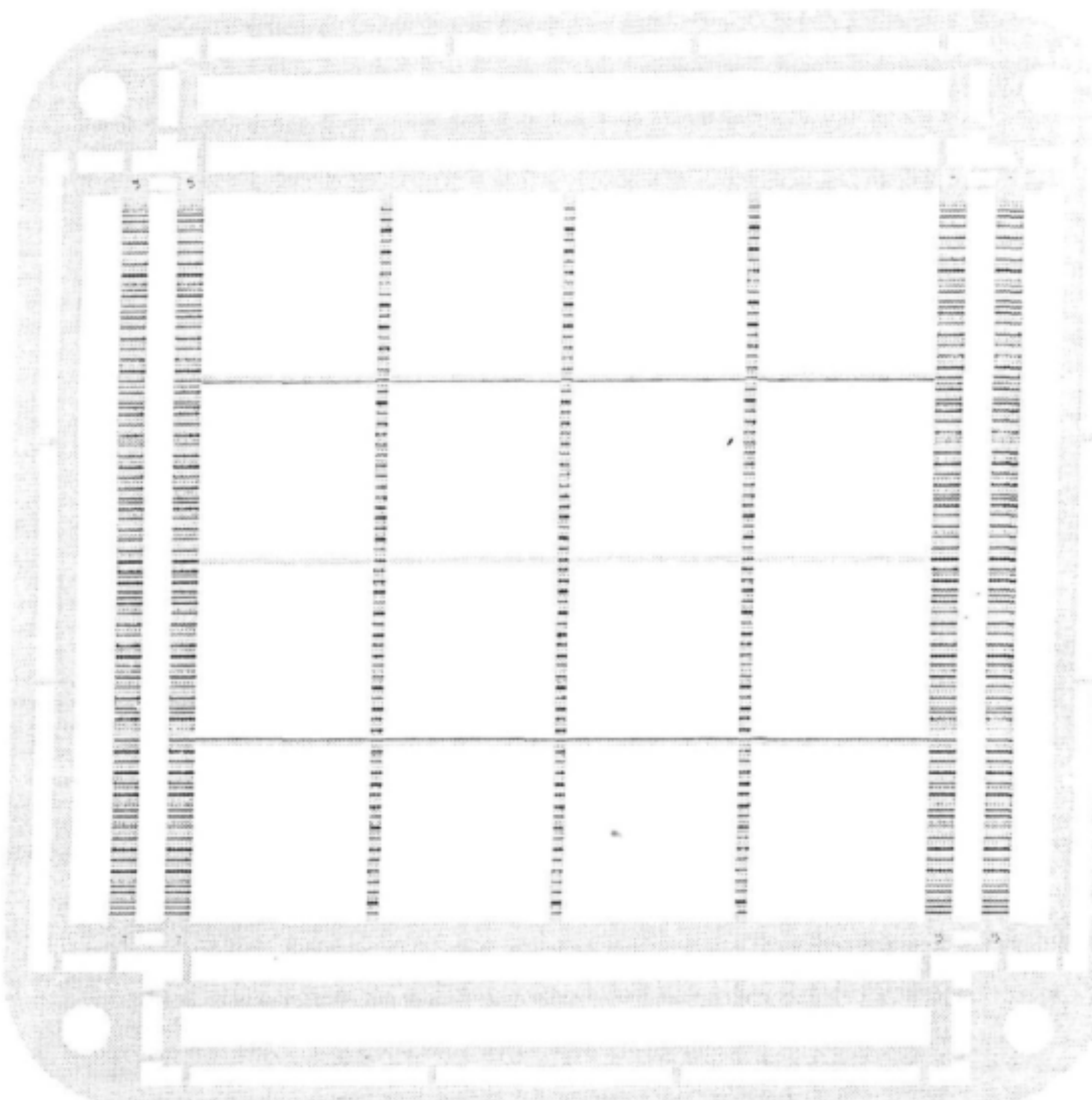


FIGURE 5.6: SPACER WITH 68 CAPILLARY-MEMBRANE LOCATING-GROOVES

SCALE UP OF PRESENT SPACER CONCEPT WITH SUPPORT LATTICE

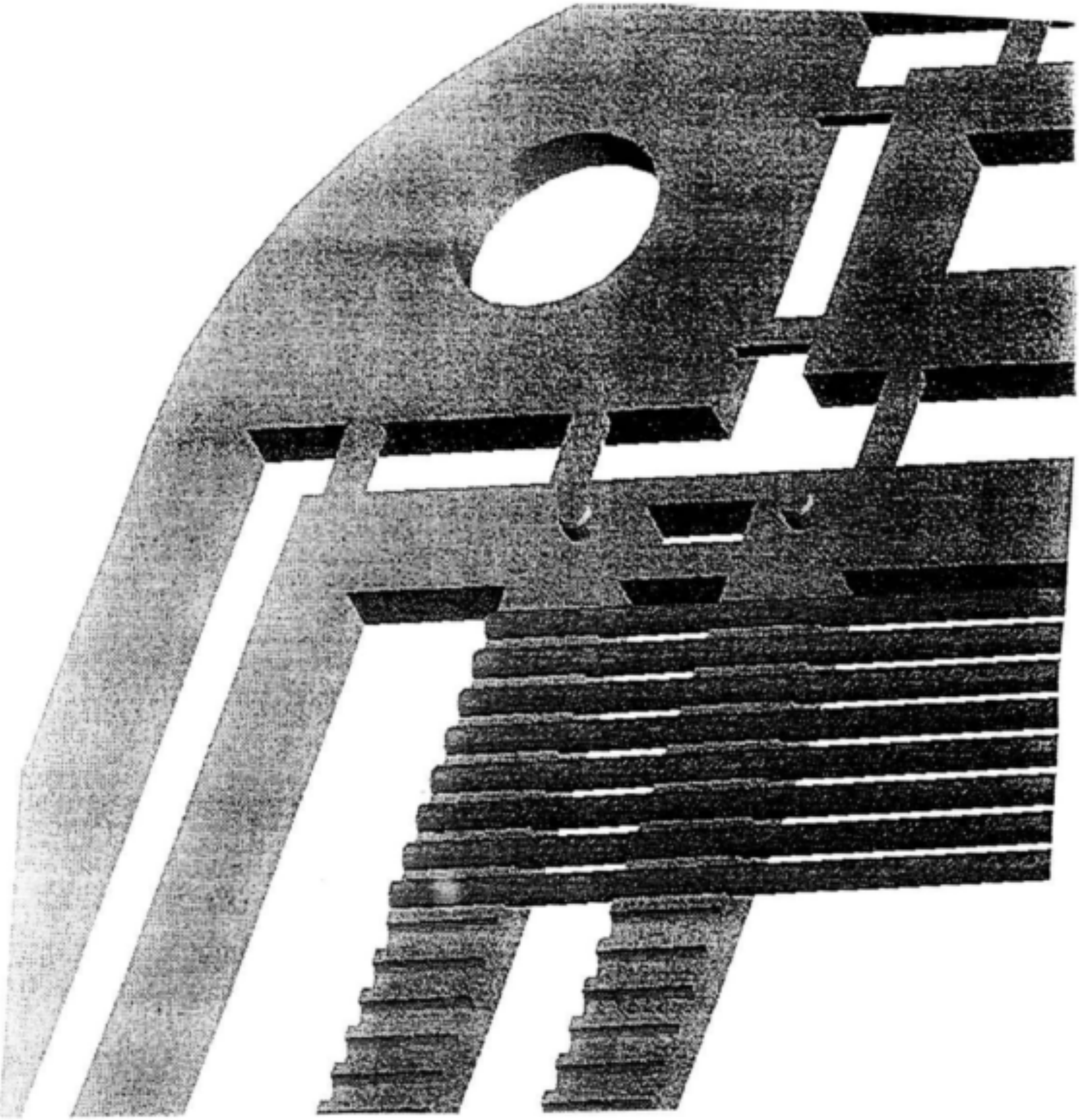


FIGURE 5.7: DETAIL OF SPACER WITH 68 CAPILLARY-MEMBRANE LOCATING-GROOVES AND SOME CAPILLARIES INSERTED

SCALE UP OF PRESENT SPACER CONCEPT, WITH SUPPORT LATTICE

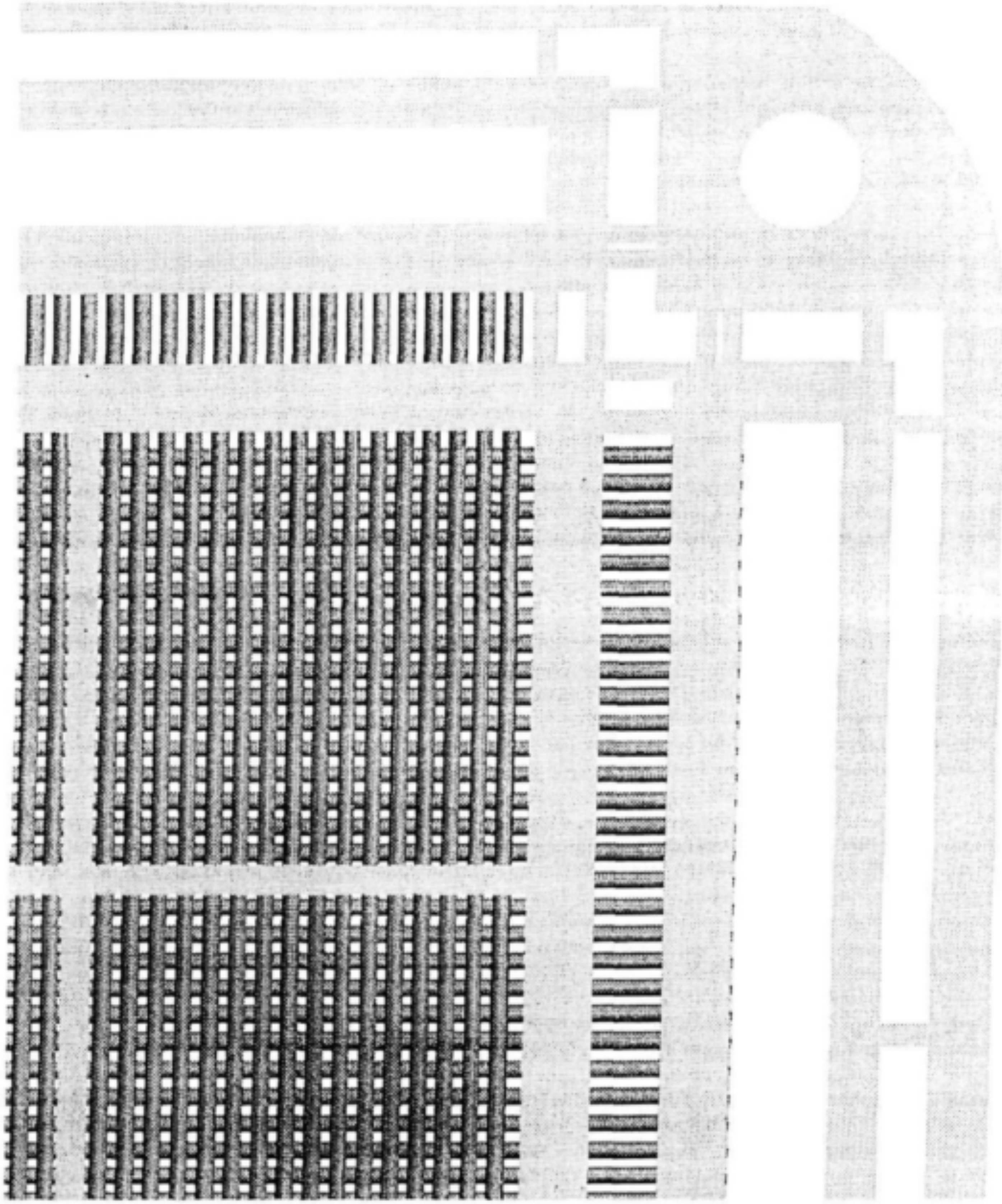


FIGURE 5.8: DETAIL OF MODULE STACK WITH TWO LAYERS OF CAPILLARY-MEMBRANES INSERTED

SCALE UP OF PRESENT SPACER CONCEPT, WITH SUPPORT LATTICE

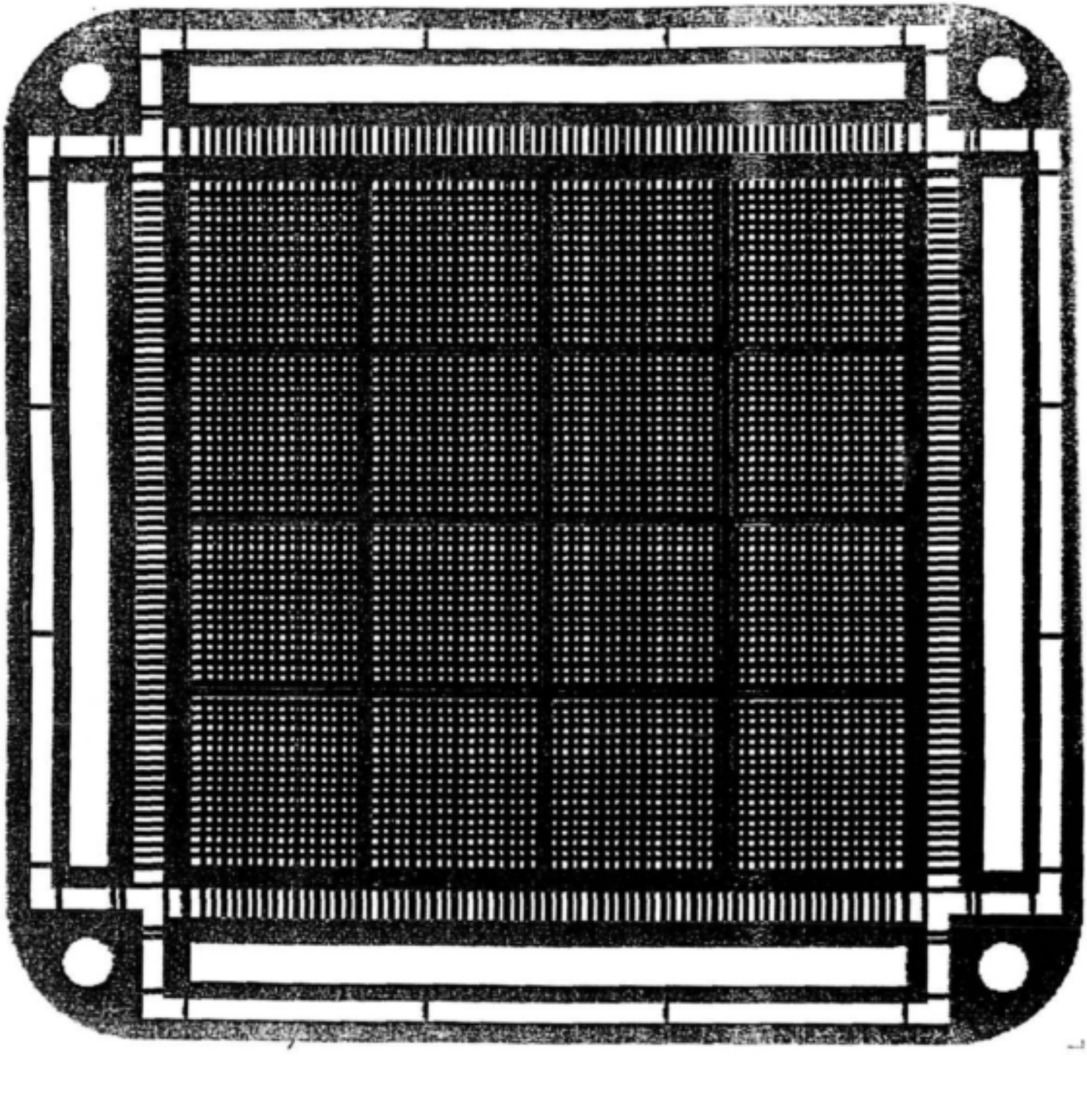


FIGURE 5.9: PLAN VIEW OF MODULE STACK WITH TWO LAYERS OF CAPILLARY-MEMBRANES INSERTED BEFORE EPOXY CASTING

SCALE UP OF PRESENT SPACER CONCEPT, WITH SUPPORT LATTICE

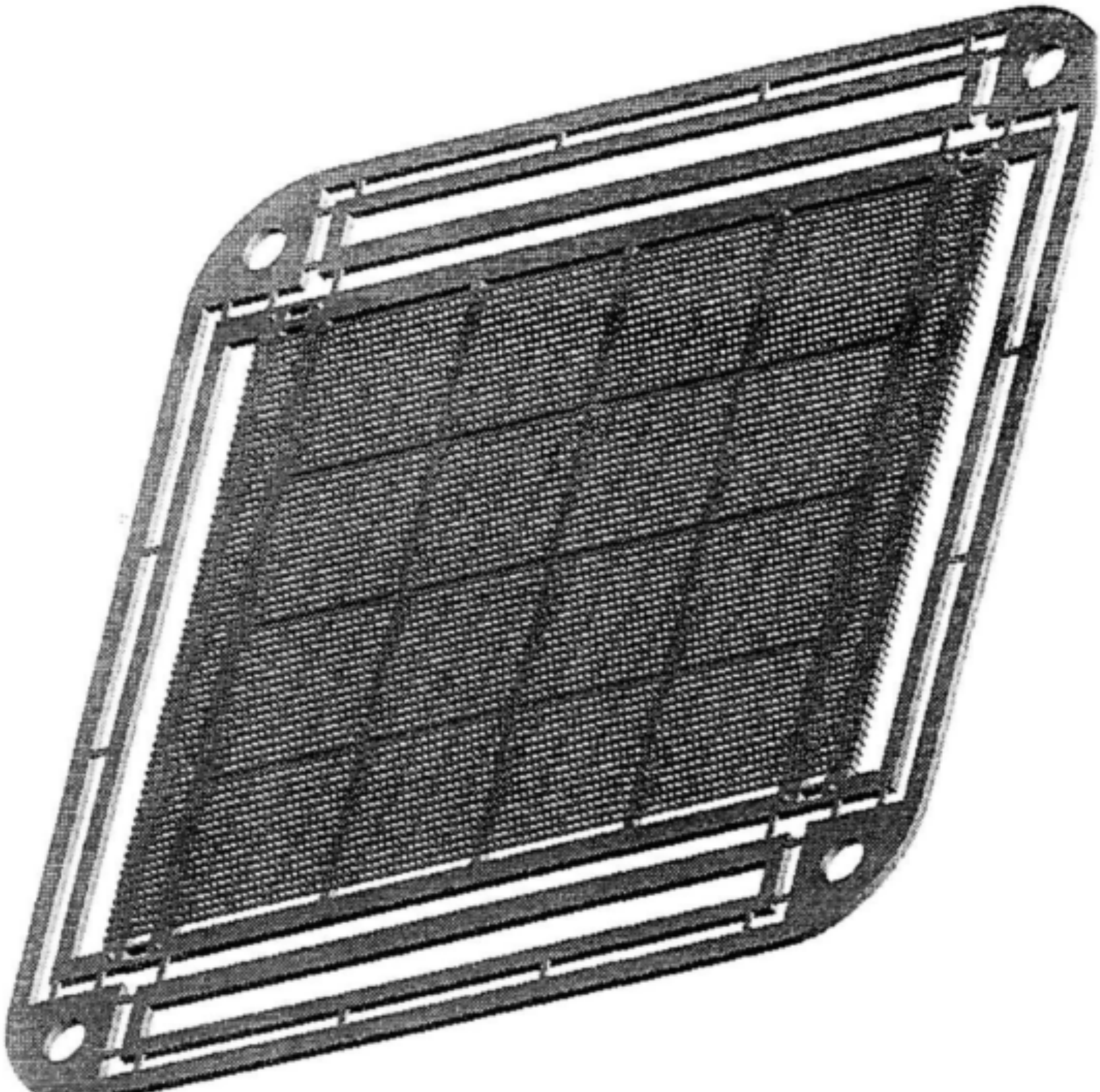


FIGURE 5.10: 3-DIMENSIONAL VIEW OF ONE MODULE SPACER WITH CAPILLARY-MEMBRANES INSERTED BEFORE EPOXY CASTING

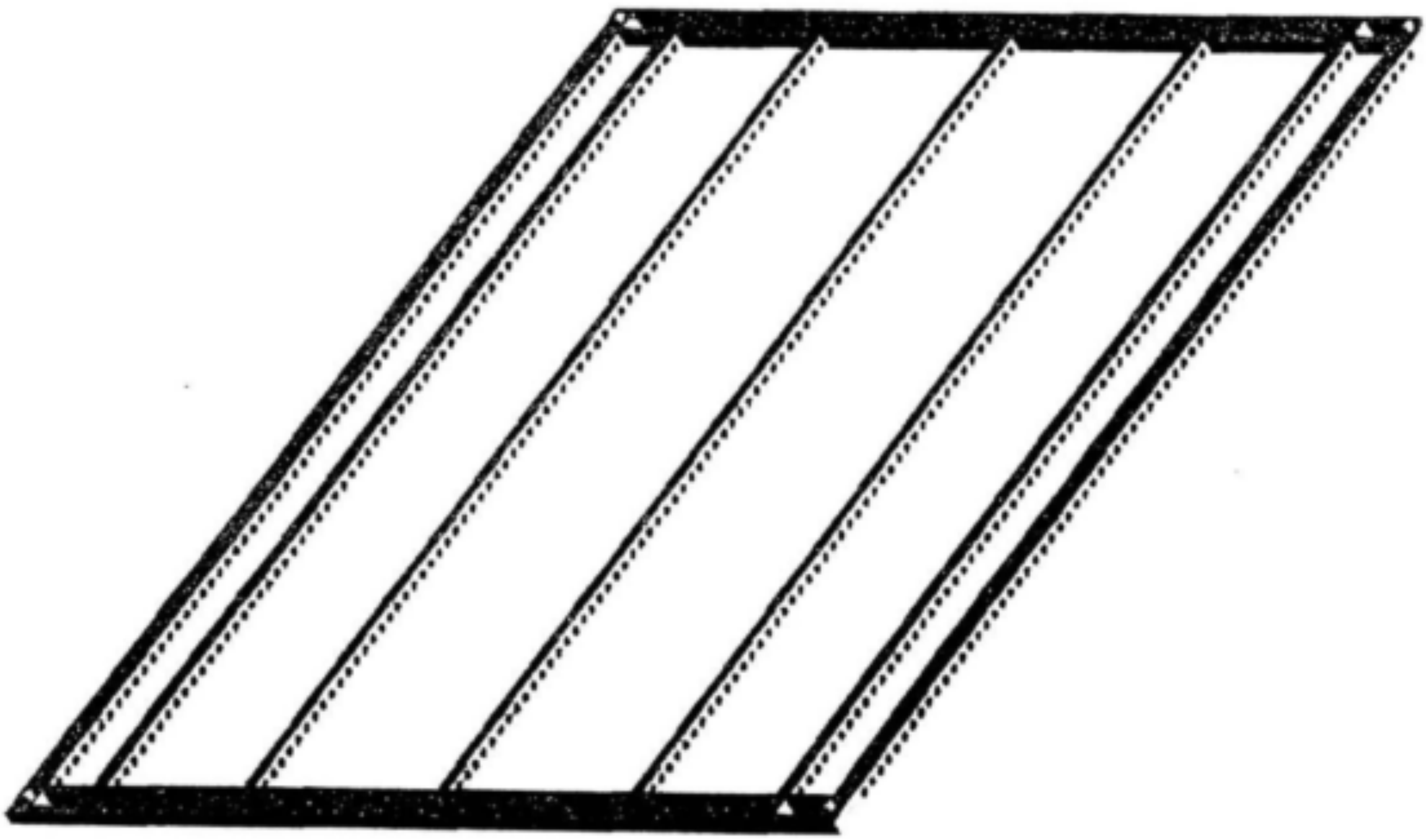


FIGURE 5.11: 3-DIMENSIONAL VIEW OF SIMPLIFIED INNER SPACER REDUCED IN SIZE, AND WITH LOCATING HOLES

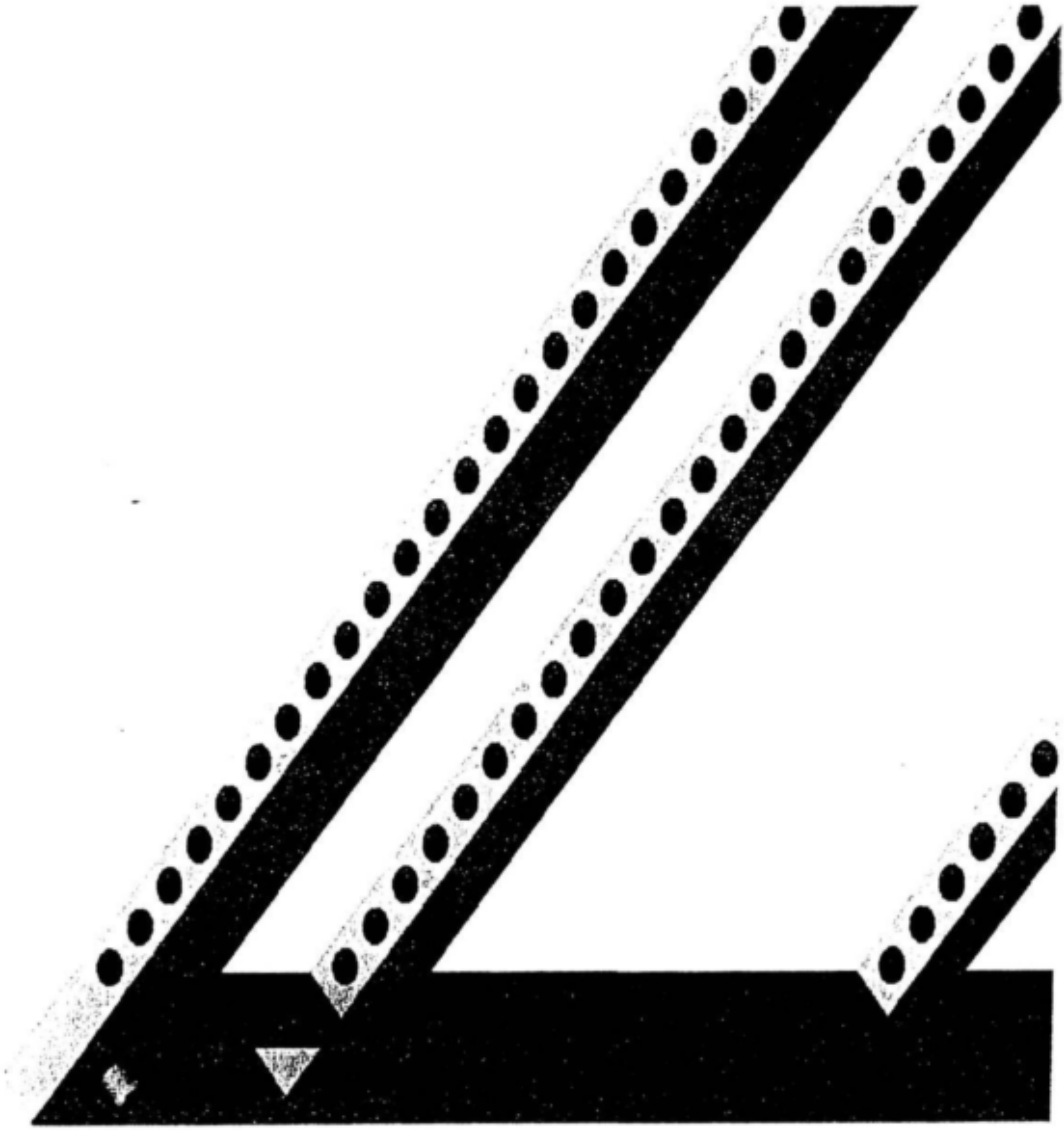


FIGURE 5.12: 3-DIMENSIONAL DETAILS OF SIMPLIFIED INNER SPACER REDUCED IN SIZE, WITH CAPILLARY LOCATING HOLES AND ASSEMBLY PINS

NEW SPACER CONCEPT

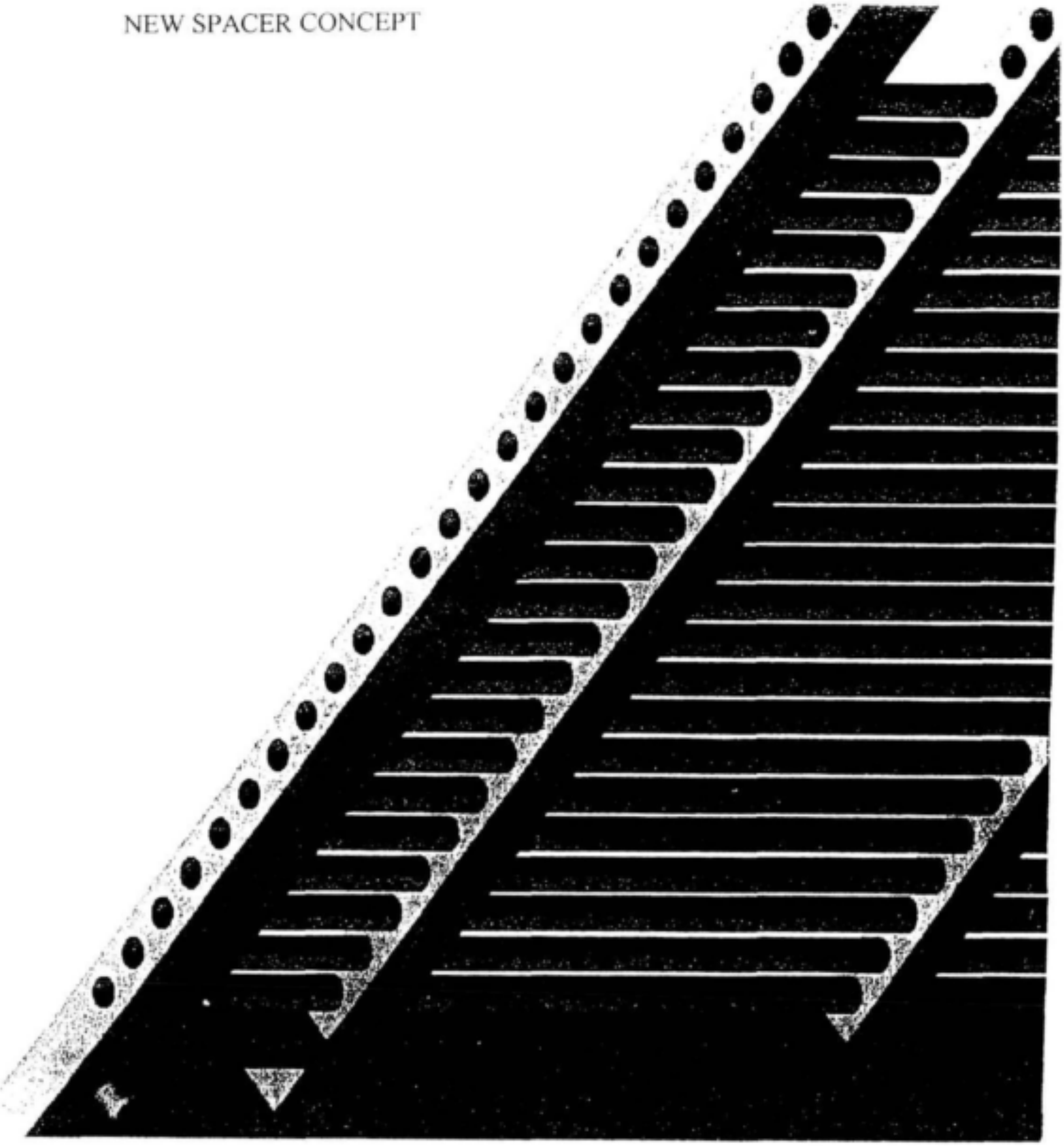


FIGURE 5.13: 3-DIMENSIONAL DETAIL OF SIMPLIFIED INNER SPACER REDUCED IN SIZE WITH CAPILLARIES IN LOCATING HOLES

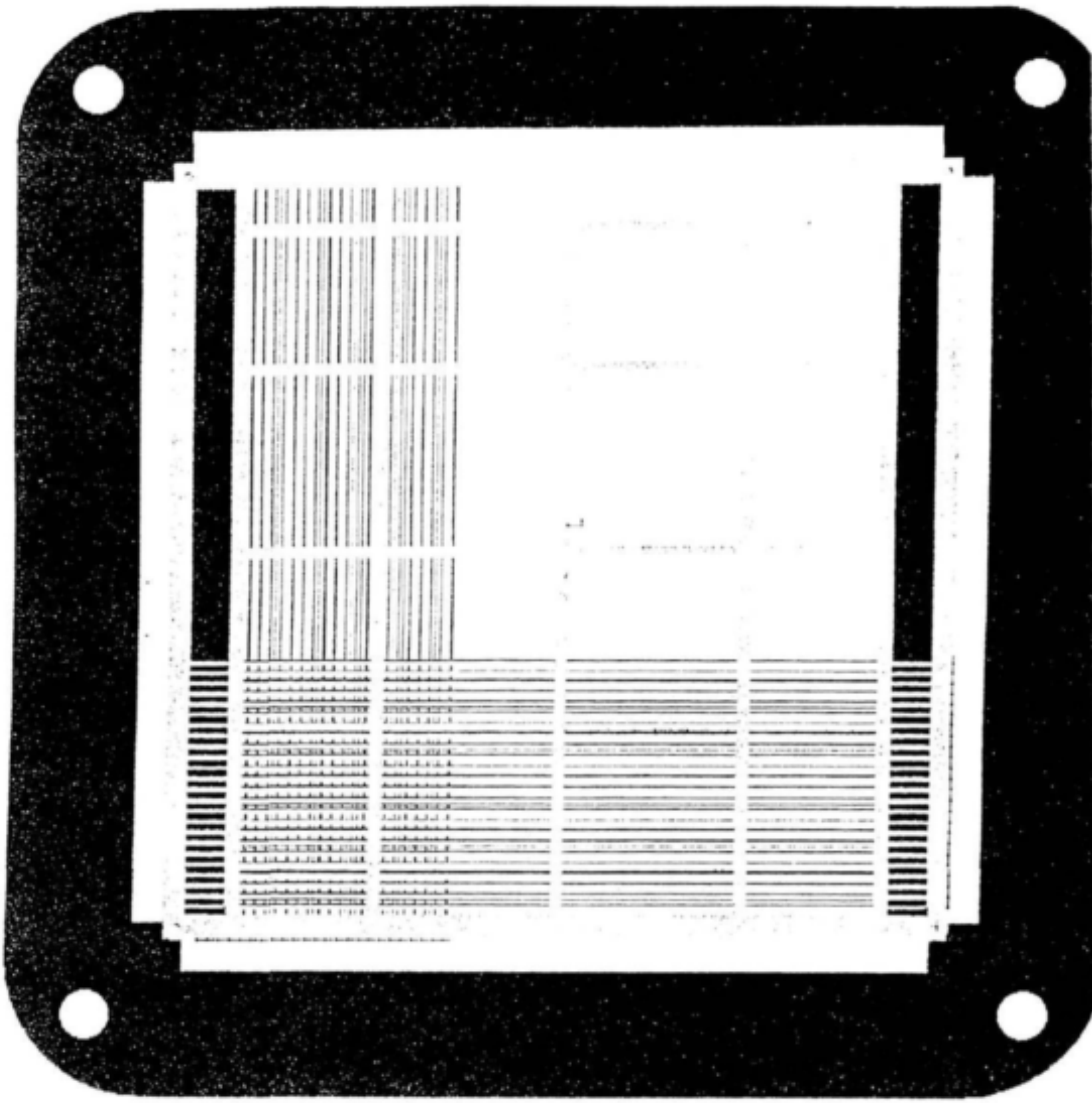


FIGURE 5.14: PLAN VIEW OF SIMPLIFIED SPACER TEMPLATE WITH CAPILLARIES IN LOCATING HOLES AND EPOXY ENCAPSULATION FORMING A HERMETIC SEALED BLOCK MODULE. (outer module configuration, 4-flow channels and 4-clamping holes formed by the epoxy encapsulation mould)

NEW SPACER CONCEPT

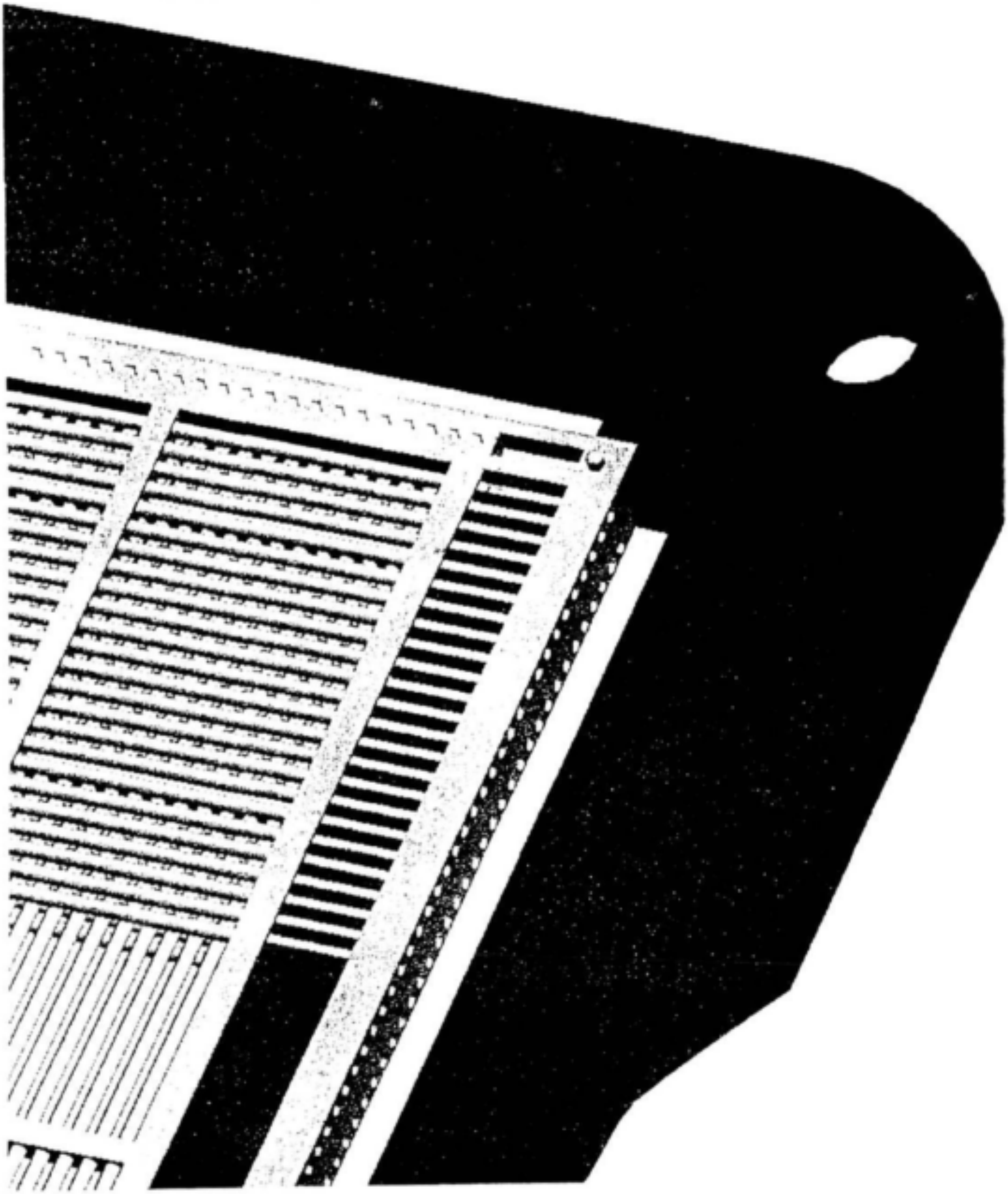


FIGURE 5.15: 3-DIMENSIONAL DETAIL DWG ILLUSTRATING THE SIMPLIFIED MODULE ASSEMBLY METHOD

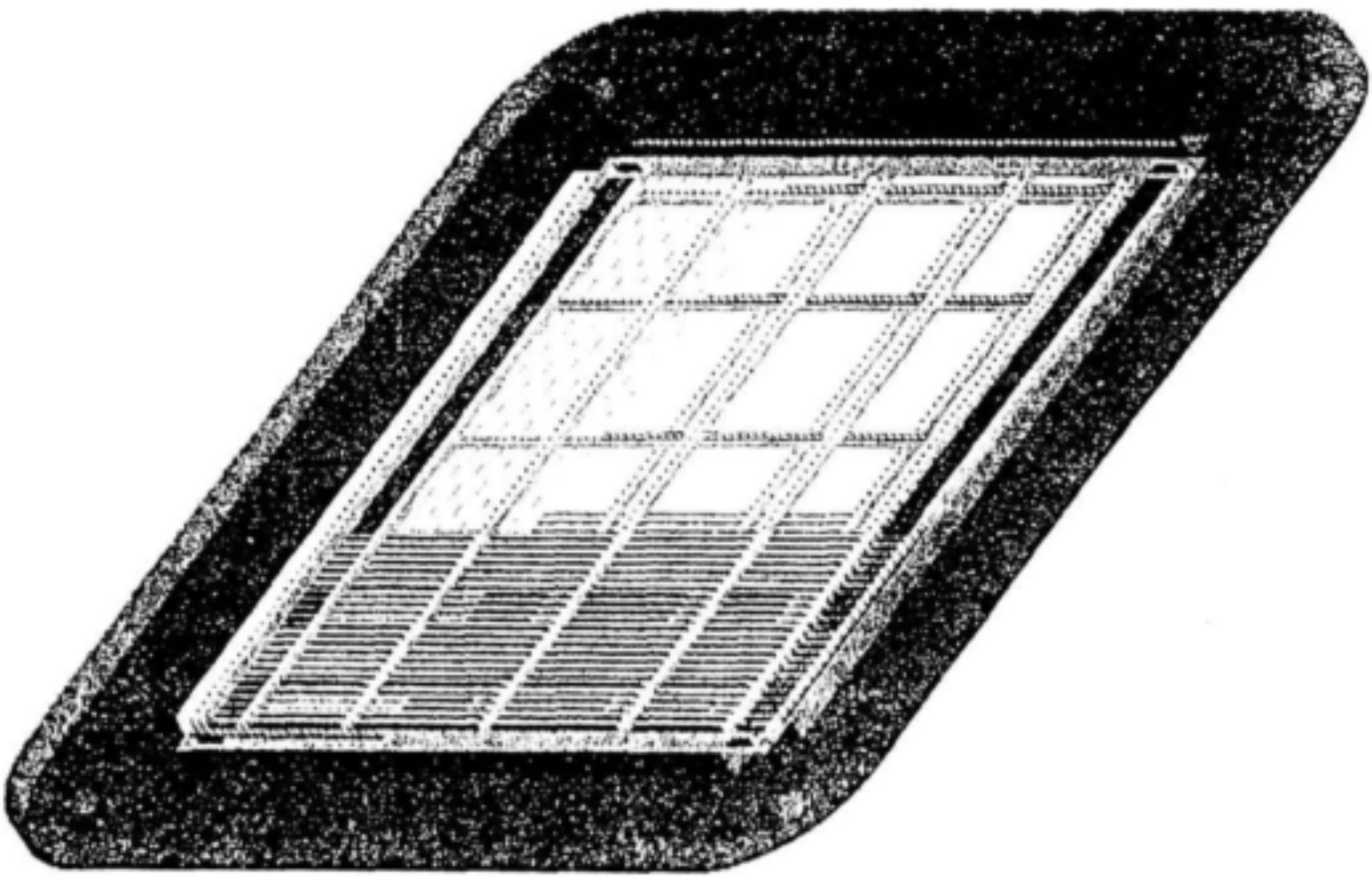


FIGURE 5.16: 3-DIMENSIONAL DWG ILLUSTRATING THE SIMPLIFIED MODULE ASSEMBLY METHOD .

ADDENDUM

COST ESTIMATES FOR THE MANUFACTURE OF CAPILLARY MEMBRANE MODULES

These cost estimates are based on the assumption that the manufacturing process is a continuous one, that the staff have the necessary production skills and that all jigs, tools, moulds and fixtures are used. The capillary membranes are the highest cost expense at present. As soon as multiple capillary membrane production spinning equipment is available, the cost of producing the capillary membranes will be reduced by about 50% if 3 spinneret production lines are used. At present the following figures make it possible to do limited cost comparisons with other water purification systems and with imported modules.

LABOUR COST ESTIMATE:
200mm diameter capillary membrane module assembly.

	TASK	HOURS
Shroud:	Cut uPVC to length	0.10
	Machine, face, chamfer ends, sealing grooves	1.00
	Drill key in holes, deburr, chamfer	1.75
	Drill permeate hole and deburr	0.15
	Degrease, roughen, apply primer to epoxy contact areas	0.50
	Apply silicon sealant into 4 grooves	0.45
	Weigh capillaries and make up to 7 bundles	3.00
	Fit centre net	0.50
	Fit outer net	0.25
	Trim and seal one end with quick-setting epoxy	1.00
	Insert into shroud and centre	0.50
	Insert into mould and assemble	0.75
	Fasten to centrifugal casting machine	0.50
	Mix epoxy and fill reservoir	0.15
	Centrifugal casting start and stop (casting time 0.45-3hrs)	0.10
	Remove and dismantle mould, extract module, clean mould	1.25
	Repeat for other end	4.25
	Cut off sealed ends	0.10
	Face ends	1.00
	Fit permeate outlet, label and O-rings	0.50
	Test module, preserve and pack	1.50
TOTAL HOURS		19.30
ASSEMBLY COST: = 19.3 h @ R30/h		R579.00

Please note the above estimate is based on a continuous module manufacturing operation with semi-skilled staff at R30.00 per hour

LABOUR COST ESTIMATE:
90mm diameter capillary membrane module assembly

	TASK	HOURS
Shroud:	Cut uPVC to length	0.10
	Machine, face and chamfer ends, and sealing grooves	1.00
	Drill key-in holes, deburr, chamfer	1.50
	Drill permeate hole and deburr	0.15
	Degrease, roughen, apply primer to epoxy contact areas	0.50
	Apply silicon sealant into 4 grooves	0.45
	Weigh capillaries and make 1 bundle	1.00
	Fit net	0.20
	Trim and seal one end with quick-setting epoxy	0.50
	Insert into shroud and centre	0.40
	Insert into mould and assemble	0.75
	Fasten to centrifugal casting machine	0.30
	Mix epoxy and fill reservoir	0.15
	Centrifugal casting start and stop [casting time 0.45-3hrs]	0.10
	Remove and dismantle mould, extract module, clean mould	1.25
	Repeat for other end	3.55
	Cut off sealed ends	0.10
	Face ends	1.00
	Fit permeate outlet, label and O-rings	0.50
	Test module, preserve and pack	1.50
TOTAL HOURS		15.00
ASSEMBLY COST: = 15.0 h @ R30/h		R450.00

Please note the above estimate is based on a continuous module manufacturing operation with semi-skilled staff at R30.00 per hour.

MATERIAL COST ESTIMATE:

200mm dia capillary membrane module assembly. Surface area $20m^2$

MATERIAL	COST(R)
Shroud: uPVC class 4; 200mm diameter R59.17/m; 1.25m	73.96
Clamp saddle	399.00
O-Rings made from 8mm diameter cord @ R60/m including glue:	
$4(225\ OD - 8)\pi = 2.73m$	163.80
Silicon sealant	15.00.
Epoxy Membralock: 4; 6.5 kg @ R55.00/kg	357.50
Capillary membranes: 5108 off; each 1.4 m long @R1.20/m	8581.45
Netlon sleeve: 125mm layflat; 3.5m @ R3.00/m	10.50
Outer sleeve: 0.5m @ R0.50/m	0.25
Quick setting epoxy: 300 gr @ R150.00/kg	45.00
MEK: 0.05 litres @ R 150.00/ litre	7.50
TOTAL	9653.96

MATERIAL COST ESTIMATE:
90mm dia. capillary membrane module assembly.
Surface area 6.5m^2.

MATERIALS	COST(R)
Shroud: uPVC class 4; 200mm diameter R59.17/m; 1.25m	16.00
Clamp saddle	25.20
O-Rings made from 8mm diameter cord @ R60/m including glue:	
$4(225\ \mathrm{OD} - 8)\pi = 2.73\mathrm{m}$	76.20
Silicon sealant	10.00
Epoxy Membralock: 4; 6.5 kg @ R55.00/kg	71.50
Capillary membranes: 5108 ; each 1.4 m long @R1.20/m	2788.97
Netlon sleeve: 125mm layflat; 3.5m @ R3.00/m	3.75
Quick setting epoxy: 300 g @ R150.00/kg	30.00
MEK: 0.05 litres @ R 150.00/ litre	4.50
TOTAL	R3025.92

COST ESTIMATE FOR THE MANUFACTURE OF
CAPILLARY MEMBRANE MODULES

CASTING SOLUTION			COST (R)
A. SOLVENT DISTILLATION (BATCH: 7.854 kg)			
Services:	Water (m^3)	0.09 @ R2.74/m^3	0.25
	Electricity (kWh)	29.25 @ R0.27/Kwh	7.90
	Gas (kg)	0.3 @ R5.00/kg	1.50
Material (NMP):		7.854kg @ R27.40/kg	176.00
Labour:		2.17 h @ R50.00/h	217.00
TOTAL			402.65
Cost per kg			51.27

B. NON-SOLVENT ADDITIVE DISTILLATION
(BATCH: 6.33 kg.)

Services:	Water (m^3)	0.09 @ R2.74/m^3	0.25
	Electricity (kWh)	29.25 @ R0.27/Kwh	0.73
Material(MC):		6.33kg @ R24.65/kg	156.00
Labour:		1.8 h @ R50.00/h	90.00
TOTAL			246.98
Cost per kg			39.02

B_1 (PEG)

Cost per kg	9.00

C. CASTING SOLUTION PREPARATION (BATCH: 2 kg.)

Services:	Water (m^3)	8.64 @ R2.74/m^3	23.68
	Electricity (kWh)	57.64 @ R0.27/Kwh	15.57
Labour:		1.5 h @ R50.00/h	75.00
TOTAL			114.25
Cost per kg			57.13

CASTING SOLUTION

Polymer (PES):	0.22kg @ R150/kg	33.00
A (NMP):	0.36kg @ R51.27/kg	18 46
B (MC):	0.10kg @R39.02/kg	3.91
B_1 (PEG)	0.32kg @ R 9.00/kg	2.88
C		40.82
TOTAL per kg casting solution		99.07

Note: 490m of capillaries 1.85 OD x 1.33 ID/kg casting solution

CAPILLARY PROCESSING COSTS

RO Process water:	$4.11m^3$ @ R5.00/m^3	20 55
Electricity:	24.08kwh @ R0.27/kwh	6.55
Consumable solvents /shift		41.00
Labour:	7hours @ R100.00	700.00
	4hours @R 50.00	200.00
TOTAL		968.10

CAPILLARY COST/m

980 m of capillaries per 8 h shift	968.10
2.00 kg casting solution per shift	198.14
TOTAL	R1166.24
Cost per meter of capillary (1166.24/980)	1,19

CAPITAL COSTS

CAPILLARY CASTING SOLUTION PRODUCTION

CASTING SOLUTION MIXING EQUIPMENT	13000.00
LABORATORY SCALE	9000.00
LABORATORY OVEN	10000.00
DISTILLATION EQUIPMENT (GLASSWARE) FOR NMP WITH VACUUM PUMP	8000.00
TOTAL	40000.00

CAPILLARY PRODUCTION

SPINNERET	2600.00
FILTER 2 OFF	2000.00
GEARPUMP (BARMAG) WITH MOTOR & GEARBOX	7500.00
FLOWMETER 2 0FF	1800.00
NEEDLE VALVE 3 OFF	3000.00
GLASS TANK: 150 x 150 x 1200mm	400.00
CASTING SOLUTION CONTAINER	1100.00
HIGH HUMIDITY GLASS CYLINDER	900.00
HAUL-OFF WITH MOTOR & GEARBOX	12000.00
SST TANK 250 x 200 x 5m LONG WITH 2 DRIVEN ROLLERS & MOTORS, GEARBOXES & STANDS	38000.00
VARIABLE SPEED SYNCHRONISED CONTROL CABINET (4-DRIVES)	20000.00

CONTROLLABLE WATER-HEATER	3000.00
CONDITIONING CABINET	900.00
RO PLANT FOR THE SUPPLY OF CLEAN WATER	10000.00
STEREO MICROSCOPE	75000.00
TOTAL	110700.00
CAPILLARY MEMBRANE MODULE PRODUCTION	
CENTRIFUGAL CASTING M/c	25000.00
CASING MOULDS: 3 OFF	8000.00
EPOXY MIXING & DISPENSING EQUIPMENT	12000.00
MODULE FACING EQUIPMENT: SUB-CONTRACT	25000.00
TOTAL	80000.00
MEMBRANE & MODULE TESTING	
MEMBRANE TESTING EQUIPMENT	35000.00
ASSEMBLY AND COMMISIONING OF PLANT	30000.00
SUB TOTAL	R295700.00
C0NTINGENCY: 20%	59140.00
CONSUMABLE MATERIALS	
EPS (ULTRASON BASF) 25KG	4000.00
SOLVENTS	2000.00
CHEMICALS	4000.00
GLASSWARE	3800.00
	11800.00
CONTINGENCY 30%	4200.00
	16000.00
GRAND TOTAL	**R370840.00**

Please note this does not include development costs of **R1 500 000,00**

COST COMPARISONS

COSTS	90mm diameter MODULE 5.5m^2	200mm diameter MODULE 20m^2
Labour	450.00	579.00
Material	3025.92	9653.96
Capital Cost Amortization	200.00	200.00
Manufacturing Cost	3675.00	10432.96
Overheads: 30%	1225.00	3129.89
Marketing: 40%	1470.00	4173.18
Total Cost	6370.00	17736.03
Profit: 40%	2548.00	7094.41
SELLING PRICE	**8918.00**	**24830.44**

COST to MODULE SIZE COMPARISON

The 200mm$^{\varnothing}$ module has 20m^2 membrane area; 3.08 times larger than the 90mm$^{\varnothing}$ module which, theoretically, has 6.5m^2 membrane area. If the manufacturing labour costs are calculated at R30/h, the 90mm$^{\varnothing}$ module is comparatively **8.38%** more expensive then the 200mm$^{\varnothing}$ module. This relationship changes drastically when the manufacturing labour costs are calculated at R100.00/h. The 90mm$^{\varnothing}$ module is then **23.39%** more expensive than the 200mm$^{\varnothing}$ module. If the membrane area of the 90mm$^{\varnothing}$ module is taken as only 5.5m^2 (actual size), the 200mm$^{\varnothing}$ module is about **30%** more cost effective.

PRICE OF THIS MODULE IN COMPARISON WITH THAT OF OVERSEAS MODULES

Polymeric membrane modules sell for about US\$900/m^2 which is approx. R4050 m^2 or R81000 for a 20m^2 module, compared to a locally-produced module of R24830.44. A local 5.5m^2 module costs R8918.00, compared with R22275.00 overseas.

This means that the cost of our 200mm$^{\varnothing}$ module is only approximately 31%, and the 90mm$^{\varnothing}$ module about 40%, of that of the overseas modules.

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