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REPORT No. 55

Seepage Control with Plastic Membranes

Part 4 - Wind Damage to Polythene Dam Liners

by

John R. Burton

JANUARY, 1962

The University of New South Wales

WATER RESEARCH LABORATORY

REPORT No. 55

SEEPAGE CONTROL WITH PLASTIC MEMBRANES - PART 4: WIND DAMAGE TO POLYTHENE DAM LINERS

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January 1962

A Report to the Water Research Foundation of Australia Limited.

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PREFACE

This is the fourth of a series of reports to the Water Research Foundation of Australia Limited on an investigation into the use of plastic films for seepage control in farm dams and small reservoirs.

This research programme was commenced early in 1957 and was substantially completed in 1961. Some handling tests and long term durability trials are continuing.

The investigation was supported by grants from the Water Research Foundation of Australia Limited, which were made possible through the generousity of Imperial Chemical Industries of Australia and New Zealand Ltd. It was initiated by Professor J.P. Baxter, Vice-Chancellor of the University of New South Wales.

This study of wind damage was made possible through the co-operation and keen interest of Mr. A.J. Horrex of North Richmond, N.S.W. Valuable assistance was also provided by officers of I.C.I.A.N.Z. Ltd., and Plastalon Ltd.

Laboratory studies in connection with the plastic membrane research programme were made at the Water Research Laboratory, Manly Vale, N.S.W. The programme is under the direction of Mr. J.R.Burton of the Laboratory Research staff.

H.R. Vallentine,
Assoc. Professor of Civil Engineering
Officer in Charge of the Water
Research Laboratory.

January 1962

SEEPAGE CONTROL WITH PLASTIC MEMBRANES - PART 4

WIND DAMAGE TO POLYTHENE DAM LINERS

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WIND DAMAGE TO POLYTHENE DAM LINERS.

1. INTRODUCTION

The first polythene dam liner to be used in Australia was installed in a reservoir at Charlton, Victoria, in 1955. This membrane was buried under 4-6 inches of sandy soil, and, whilst the project was not successful because of an inadequate jointing technique, the plastic material itself appears to have satisfactorily withstood mechanical damage from wind, traffic, wave action or stress concentration. Following the development of successful heat-sealing methods by I.C.I., and Plastalon Ltd., several dams were lined with prefabricated heat-sealed membranes during late 1957 and in 1958, and it is reported that a total of about 20 dams and tanks have been treated in this way. So far as is known none of these liners has been buried, and it has generally been held that such protection is not essential.

Research into the possible life-expectancy of plastic membranes has been concerned principally with the effects of ultra-violet oxidation and weathering and with biological damage caused by plants, yabbies and burrowing animals. The behaviour of some of these exposed liners, notably those at Ouyen in Victoria and the one more recently installed at North Richmond in N.S.W., has now suggested that damage resulting from wind action may restrict the life of a polythene membrane more seriously than any other factor. This was particularly apparent at North Richmond, where the membrane developed signs of wind damage within a few weeks of its installation and was finally destroyed by strong winds after a life of less than four months. This paper seeks to draw the attention of those concerned with the use of polythene dam liners to the importance of wind damage and to suggest ways in which this form of mechanical attack might be counteracted.

2. HISTORY OF THE NORTH RICHMOND PROJECT.

2.1 Installation of the Liner.

Early in June 1958 Mr. A.J. Horrex of North Richmond, N.S.W., approached I.C.I.A.N.Z. and Plastalon officers in Sydney with a proposal to instal a polythene liner in a small dam on his property. This dam is circular in shape and has a capacity of 200,000 gallons; a contour plan and storage-elevation curve are shown in Figures 1 and 2. The dam is located on the brow of a hill commanding steep slopes on which flowers and vegetables are cultivated. Its purpose is to act as a service reservoir for irrigation purposes, being filled by pumping from a large gully dam at a lower level and emptied through a low pressure gravity sprinkler system.

The dam is constructed of a shale-clay mixture which under normal circumstances could be expected to be reasonably impervious, but leakage occurs through the floor, which appears to intersect faulted shale, and through a section of the embankment which had been re-compacted following the installation of an outlet pipe. It was reported by the owner that before lining the dam would empty over a period of about three weeks. Measurements made after the failure of the liner however showed a drop in water level of only six inches per week from seepage (See Figure 7) indicating that the dam would take nearly six months to empty from the full condition.

Following negotiations with Plastalon Ltd., an 0.004 inch black polythene membrane was prefabricated, using the factory heat-seal process developed by that firm. The liner was installed in the dam on Wednesday 25th June, 1958, under the direction of officers of Plastalon Ltd., details of the installation being completed next day by the owner himself.

Three unforeseen difficulties arose during the lining operation. In its original condition the inner face of the dam was freely covered with loose particles of sharp shale. An attempt was made to place a sand cushion over this material, but because of a hold-up in the delivery of the sand it was possible only to cover the floor of the tank and the western and northern sections before the liner was placed in position. This was remedied on the following day, when the liner was folded back and sand spread over the remainder of the inner face. The initial filling of the dam on June 25th. brought the water level to a depth of 3 feet only, and the area of membrane underlain by stoney material was therefore not subjected to hydrostatic pressure. The condition of the inner face of the dam after the destruction of the liner on October 11th, indicated that the cushioning was in fact carried out in a satisfactory manner, and there was no noticeable evidence of piercing of the membrane by underlying material.

A second difficulty arose with the necessity for sealing the liner around the outlet pipe, a 4 inch diameter galvanised pipe which protrudes into the tank just above floor level on the southern side. This seal was achieved simply by cutting a circular hole in the membrane and securing it around thepipe with Bostick adhesive and Polykin tape. The seal subsequently gave way and was responsible for seepage losses from the tank.

A third difficulty arose in the handling of the prefabricated membrane. When the packaged membrane was first unrolled on the site it was found to be incorrectly positioned in relation to the shape of the tank, and it was therefore necessary to re-roll and reverse the liner and carry it to another part of the tank before pulling the material into its final position. This additional handling resulted in some puncturing of the liner, due to unavoidable trampling by members of the handling team. When the membrane was pulled into place it was noted that a length of welded seam on the south-eastern side, near the crest of the embankment, had pulled apart, and a temporary seal was not a success; several attempts to repair the damage were made in the weeks which followed, during which time the opening increased in size until it extended across a large part of the eastern side of the membrane. The results of this mishap are also discussed in detail in a later section.

The lining operation commenced about 2.30 p.m. on June 25th., and once the initial upset had been overcome the liner was pulled into position in about ten minutes. After it had been temporarily anchored around the perimeter of the tank the sealing around the outlet pipe was effected. At the same time a Bristol water level recorder bulb and tube were installed in the pond and a 6 ft wide strip of 0.004 inch black polythene was laid from crest to floor on the southern side for experimental purposes. Filling of the pond was then commenced, the pump being started at about 3.30 p.m. The water level in the tank rose to about 3 feet by 4 p.m., at which time filling was discontinued as the result of a pump breakdown. During this initial filling the membrane was eased into place around the sides of the tank and provisionally secured in the anchor trench.

On the following day, June 26th., the liner was partly folded back and sand spread over those parts of the inner face which had not been cushioned on the previous morning. The memerane was then pulled nestly into shape and securely anchored in a trench around the inner perimeter of the embankment crest, which was backfilled and compacted with a tractor tyre. At the same time the construction of an overflow apron was commenced on the north-western side of the tank to prevent overfilling. This apron was not complete before the destruction of the liner.

2.2 Subsequent History up to Time of Failure.

Because of a pump failure the tank was filled only to a depth of 2 feet on the day of installation. Subsequent trouble with the pump and the difficulties experienced with the faulty seam on the eastern side interfered with the filling operation, and the water level was slowly raised by intermittent pumping to a maximum depth of 11 feet, which was not reached until July 31st. No further pumping was undertaken during the life of the liner. It might be noted in passing that an article describing this project which appeared in "Pix" magazine on August 16th., stated that the dam had been filled to a depth of "more than 40 feet" within "a few hours" of the placing of the liner!

Figure 3 shows a record of water levels in the dam up to the time of failure. The weekly charts from the water level recorder began to give evidence of seepage loss around July 21st., and visible signs of seepage around the outlet pipe on the southern toe of the embankment were evident by July 25th. After pumping was discontinued on July 31st., the drop in water level from seepages losses became more apparent, and seepage flow from the toe of the embankment became more obvious, portion of the toe becoming saturated and water commencing to flow slowly away from a collecting drain on the downhill side of the dam. This flow increased in quantity until eventually a considerable amount of seepage water collected in the table drain along the access road to the tank. After August 1st., the water level in the tank fell steadily, because of seepage losses; during the following week, August 1st., to August 8th., seepage accounted for a drop of approximately 9 inches, after allowing for evaporation loss. The rate of seepage loss decreased progressively as the depth of water in the tank became smaller, but seepage losses continued to be evident up until the destruction of the liner.

On August 1st., the writer attempted unsuccessfuly to locate the source of this seepage loss by using trace dyes. On September 12th., the underwater sections of the membrane were briefly inspected, using diving equipment, and it was discovered that the membrane had pulled away from the outlet pipe, leaving a large opening through which water could pass to the underside of the liner. It is considered that the major part of the observed leakage from the liner occurred through this opening.

After seepage losses had become evident and attempts to locate their source had proved unsuccessful the owner was advised to empty the tank in order to permit a visual examination of the whole of the membrane material. It was not convenient for him to do so until September 23rd., by which time seepage and evaporation losses had reduced the level in the tank to 7 feet. Between September 23rd. and October 11th., water was used for irrigation at intermittent periods, and on the morning of October 11th., just before the rupturing of the membrane took place, the level in the pond stood at 3 ft. 9 in.

The membrane suffered cumulative wind damage through its life. The seam on the eastern side which had opened during the installation of the liner was a particular source of trouble. This opening was sealed unsuccessfully with Polykin tape on July 25th., and a number of other unsuccessful attempts to repair the damage were made during the weeks which followed. Wind action progressively lengthened the opening during this time and during the week preceding July 19th., it extended to form a right-angled tear which exposed a large area of the embankment around top water level. This tear was eventually sealed with polythene film and Poly-Grip adhesive on July 28th.

The dam is sited in a particularly exposed location and strong, gusty winds were frequently experienced. By early July wind damage was evident over the eastern part of the liner, which was exposed directly to the predominantly westerly winds. This damage took the form of stress cracking and fatigue holing, and was particularly noticeable along the original centre-folds in the polythene sheet. There was no distinct evidence of mechanical damaging from stones or animals, nor of oxidative weathering, during the life of the liner.

2.3 Failure of the Membrane.

On Monday October 13th, the writer received a telegram from the owner reporting that the membrane had been severely ruptured in a wind squall on the previous Saturday, October 11th, The site was inspected with Horrex on October 14th., and the extent of the damage at that date can be gauged from the photographs which accompany this report. Strong winds experienced subsequent to October 14th., caused further damage, and the liner was later removed from the tank, being beyond repair.

From the water level recorder chart it has been established that the rupture took place about 1 p.m. on October 11th., which was a day of storms and sudden squalls. It will be seen from Figures 4 and 5 that the membrane tore into three pieces. The centre piece remained in position in the tank, where it had been protected by the water and by a number of submerged sandbags. The eastern and western portions tore along welded seams running approximately north and south and tore or pulled out of the ground around the line of the anchoring trench. Some idea of the strength of the wind may be gauged from the way in which the liner pulled cleanly out of the trench in a number of places.

The eastern portion of the membrane was blown out of the tank, damaging the water level recorder and the measuring gauge on the evaporimeter. This portion was inspected on October 14th., and it was clearly evident that it had parted from the remainder of the membrane along a line immediately adjacent to a welded seam. (Fig.6) The western section of the liner was in two pieces, having ruptured along two or more parallel seams and torn around the perimeter. Most of this material has been blown into the bottom of the tank. It is apparent from the photographs that the membrane was entirely beyond repair.

It is not difficult to reconstruct the process by which the actual rupture of the membrane took place. Horrex, who saw the damage from some distance, statedthat the trouble started on the eastern side, probably as a result of billowing of the membrane accompanied by partial opening of the large patch on this side. The forces developed by the billowing action were sufficient to tear away the eastern section along the waterline. It was then possible for the wind to lift the remainder of the membrane and the damage to the western section followed.

2.4 Research at the Site.

Because of the close proximity of the site to Sydney and the co-operation offered by the owner, Mr. Horrex, and the manufacturers and fabricators of the plastic film used, the installation and behaviour of this membrane were closely studied by the writer, as part of a research investigation being conducted by him at the University of New South Wales. A Bristol water level recorder was installed in the tank on June 25th., and a continuous record of water levels from June 25th. to October 11th. has been obtained (Figure 3). A rain

readings for these instruments are also available for the same period. The tank was visited at weekly intervals and the condition and behaviour of the membrane were been closely observed. Black and white photographs and Kodachrome transparencies were made which cover the whole history of the liner, and these were supplemented by 16 mm. movie films of the installation procedure and the damage suffered on October 11th.

On June 25th, a strip of 0.004" black polythene, 6 feet in width, was placed on the southern face of the dam, overlying the membrane itself and extending from the crest of the embankment to the floor of the dam. It was originally intended that this strip be used to investigate weathering under field conditions, by cutting samples from it at regular intervals and checking them for degradation. Owing to the high winds experienced at the site this strip was frequently blown out of position, and it was only correctly exposed for about half the life of the liner. The remains of the damaged liner itself were, however, made available to the University and samples were subsequently tested for weathering strength loss and wind damage. (See section 3.3)

3. PERFORMANCE OF THE LINER AT NORTH RICHMOND

3.1 Seepage Losses.

A record of water levels in the Richmond tank from the day of installation to the day of failure is shown in Figure 3.

As explained in the foregoing section, the pond was not filled completely until July 31st., because of mechanical breakdowns with the pumping system and the difficulties of sealing the large tear on the eastern side of the membrane. Evidence of definite seepage loss became apparent some days before the maximum water level was reached, and this seepage continued at about the same rate until the liner was destroyed.

During the filling period pumping was intermittent, and the dam was held at water depths of 5 feet, 7 feet, and 9 feet for periods of about a week. During these periods no detectable seepage loss was recorded.

The maximum level reached on July 31st was 12 feet on the Bristol gauge, corresponding to a water depth of 11 feet and a water volume of 150,000 gallons. During the 8 weeks between July 31st and September 23rd. the water level fell 4 feet. The nett evaporation over this period was 6 inches, and the volume of water lost from seepage was 80,000 gallons, representing 10,000 gallons per week.

In January 1959, after the removal of the liner, check water level records were taken to determine seepage in the unlined condition. Curves showing seepage rates with and without the membrane are shown in Figure 7. In the 8 week period commencing 6th. February 1959 the volume of water lost from seepage was almost exactly the same as that recorded during an equivalent period in August and September 1958. The liner was therefore completely ineffective over the latter half of its life. At this rate the dam might have been expected to empty from the full supply level in about 4 to 5 months, suggesting that the expense of a polythene liner could not have been justified; it might have profited Horrex better to have spent the money on repairs to his pump.

An investigation into the reasons for the failure of the membrane to control seepage was not completed. It is reasonably certain, however, that the major part of it occurred through the faulty seal around the outlet pipe in the floor of the dam. The underwater examination conducted by the writer on September 12th., was hampered by cold and poor underwater visibility, and it is perhaps possible that other openings in the membrane were contributing to seepage loss. Some seepage may have occurred through the patch over the tear on the eastern side until August 15th., after which date the water level in the pond fell below the level of this patch.

Additional seepage may also have taken place through small punctures and worn holes on the upper part of the membrane, particularly on the eastern side and in the vicinity of the Bristol recorder capillary tube. Because of the small total area of these holes and the low hydrostatic head acting on them the loss from this source is considered to have been small.

It should be emphasised, however, that the damage due to wind action grew steadily worse throughout the life of the liner, and if allowed to go unchecked this would almost certainly have resulted, by the end of 1958, in tearing and

disintergration over much of the upper part of the liner on the eastern side. The same effect was observed late in 1958 on the large tank at Ouyen in Victoria, which had been in service for one year and was then extensively holed above the water line. Seepage losses through a membrane damaged in this way might be considerable in the full-tank condition, particularly if the membrane is not buried and the underside space becomes entirely filled with water.

It is not certain at what date the seal around the outlet pipe first gave way. In view of the rather inadequate sealing technique used to secure the membrane to the pipe on June 25th., and the immediate filling of the tank to a depth of 2 feet before the adhesive used had had time to harden properly, it is possible that the seal opened to some extent on the very first day. It is apparent that the greatly increased hydrostatic pressure produced when the dam was eventually filled resulted in some shifting and stretching of the membrane, causing it to pull completely away from the pipe. This probably occurred about July 21st., Horrex reported having seen water under the membrane whilst patching the large tear during the last week in July. The we for careful sealing of any openings in the membrane is obvious.

3.2 Wind damage

As explained above, the seepage losses recorded at North Richmond were due primarily to a faulty seal around the outlet pipe, and the short life of the liner did not permit a proper evaluation of the long-term seepage control behaviour of the membrane. The outstanding lesson to be learnt from this project was the totally unexpected effect of progressive wind damage to the liner, which caused a rapid deterioration of the polythene and contributed to the ultimate destruction of the membrane.

Four distinct forms of wind damage were observed, as follows:-

a. Lifting and stretching of the membrane.
b. Cracking and holing from fatigue breakdown.
c. Holing from wind-induced abrasion
d. Tearing, particularly along the welded seams.

Lifting and stretching is a primary form of damage which does not, of itself, impair the water-holding properties of the membrane. It is, however, responsible for the secondary effects of fatigue and abrasion holing, or, if stretching becomes excessive [illegible]

damage, therefore, is to reduce or eliminate lifting or stretching by anchoring the membrane in some way.

When the membrane at North Richmond was installed on June 25th., a tear about 5 feet in length was discovered along a seam near the crest of the dam on the eastern side, and was presumably the result of faulty welding. When the tear was noticed an attempt was made to seal it using a strip of "Polykin" tape. This was not effective, and a number of other unsuccessful attempts to patch the break were made during subsequent weeks. Wind action caused the tear to increase in length, and during the week preceding July 21st., strong winds enlarged it to form a large triangular opening along and at right angles to the original failed seam. The break was eventually patched on July 28th., using long strips of polythene film sealed with "Polygrip" adhesive. As a result of the stretching and crinkling suffered by the material adjacent to the tear a neat seal was not obtained, and it seems likely that air and water were able to pass through the patch to the underside of the membrane.

Strong winds were frequently experienced over the period during which the tear was open, producing lifting and billowing on the eastern side of the liner. The aerodynamics of the site were such that a strong westerly wind appeared to create suction along the eastern face, thus accentuating billowing in this area. The effect was cumulative; billowing caused some stretching, which then permitted more billowing than before and led to greater stretching. Thus, after the tear had been closed, aerodynamic billowing continued and gradually became accentuated; this seems to have contributed more to the final rupture of the memorane than the early effects of the torn weld.

It was observed that direct sunshine on the black polythene film was heating the material to a stage where softening and stretching could occur. It is possible that this heating produced a slight pressure differential beneath the membrane, thus further accentuating the billowing problem.

Subsequent to the failure of the dam temperature measurements under exposed black polythene film. Samples of various thicknesses were made in Sydney to determine the possible effects of heat absorption from the sun. It was found that on hot, clear days, with a shade temperature in excess of 100 degrees, the temperature of the polythene film became approximately 40 degrees higher than the shade temperature, the maximum film temperature recorded being 147 degrees with a shade temperature of 105 degrees. In cooler weather, with shade temperatures of the order of

80 degrees, film temperatures as high as 120 degrees were recorded, so long as the sky was clear. Air temperature readings on either side of the film, on hot summer days, varied by about 10 degrees, being hotter under the film. It is therefore reasonable to expect that in summer in country areas of N.S.W. an exposed black polythene membrane may frequently reach a temperature of 150 degrees and that a temperature of differential of about 10 degrees may exist across the film.

Figure 8 shows the effect of temperature on the tensile strength of polythene. It will be noted that tensile strength falls off rapidly as temperature increases, and that at 150 degrees Farenheit the ultimate tensile strength is approximately 800 p.s.i., or only about 40 percent of the strength at 75 degrees Farenheit.

Of greater significance in dam liners is the effect of temperature on the yield point. The upper curve in Figure 9 shows a stress-strain curve for polythene at 70 degrees Farenheit. At normal temperatures polythene behaves more or less elastically under stress up to a well-defined yeild point, beyond which it deforms plastically at constant stress to elongations of the order of 300-400 percent before breaking. At higher temperatures the yield point becomes less well defined, until at about 175 degrees Farenheit the softening point is reached and the material becomes plastic under all stresses. At 150 degrees Farenheit, as shown in Figure 9, plastic deformation commences at very low stress values, 20 percent elongation occurring at a stress of about 400 p.s.i. or approximately half the tensile strength at this temperature. This stress represents a loading of less than 20 pounds per linear foot on 4 mil film. It is obvious that quite moderate wind forces may develop membrane stresses sufficient to produce marked stretching and slackening in a black liner exposed directly to the rays of the sun.

To summarise the foregoing discussion it should be repeated that where black polythene liners are used in exposed, windy locations, winds blowing across the membrane surface can be expected to promote billowing. In hot sunshine the billowing may be accentuated by increased air pressure beneath the membrane, particularly if the aerodynamics of the damsite are such as to produce reduced pressures over some part of the liner. Stresses induced by billowing will cause permanent stretching; this will result in more extensive billowing and lead to greater and greater stretching. The whole effect may be quite pronounced

Billowing and stretching may cause or be associated with rapid flapping of the film and are directly responsible for the secondary effects of fatigue and abrasion holing observed at North Richmond. The cracks and holes produced in this way act as convenient starting points for tearing, particularly at high film temperatures. No data on the effects of high temperature on tear strength are available; it might safely be assumed, however, that tear strength reduces in the same degree as yield point. Strong gusty winds blowing across a liner in this condition must therefore be expected to cause some tearing and rupturing of the membrane.

The secondary effects of fatigue and abrasion holing became well established at Richmond during the four months the liner was in use. Fatigue holing appeared to be the result of the beating or rapid vibration of the film which accompanied billowing in strong winds. It was first indicated by a criss-cross pattern of fatigue cracking, which was followed by slitting or holing along the axis of the crack pattern. The phenomenon occurred particularly along lines of weakness or stress concentration; it was most in evidence along the centrefold of each strip of polythene on the eastern side. It might be noted that Lauritzen and Haws observed a similar phenomenon on their early field liners in Utah.

It should be emphasised that this fatigue holing developed very early in the life of the liner. A note in the writer's diary dated July 19th., - this is, only 24 days after the installation of the membrane - refers to extensive fatigue and abrasion holing around the upper north-eastern part of the liner.

Abrasion holing was associated with fatigue holing; it was produced by rubbing or flapping of the film against objects such as sandbags or, in some instances observed, by rubbing of adjacent folds of polythene, particularly where excessive stretching had wrinkled the material. It was most noticeable along the capillary tube of the Bristol recorder, where extensive wear was observed by July 19th. This section was subsequently protected from further damage by wrapping the tube in hessian.

The fourth form of wind damage, tearing, was not observed at Richmond until the day of failure, and this phenomenon will be discussed in detail in the next section of this report. The condition of the Ouyen liner in October 1958 suggested that when fatigue and abrasion

if the correct conditions of high wind and high film temperature occur.

It appears then that wind damage takes place in three phases; firstly, billowing and stretching of the film, which may be accentuated by any mechanical damage which has occurred; secondly, and as a result of this billowing, fatigue and abrasion holing; and finally, rupture of the membrane as a result of tearing, originating from fatigue or abrasion holes and other weakened areas such as punctures or weakened seams. A study of the behaviour of the Richmond liner and the Red Hill and Ouyen liners in Victoria suggests that where exposed membranes are used in conditions of high temperature and strong winds a severely limited service life can be expected: for 4 mil black polythene this may be less than 12 months.

The effectiveness of the water in the pond in controlling wind damage should be mentioned. At Ouyen the water level was maintained appreciably constant over a period of 12 months; wind damage was confined to the area above the water line, where, it should be emphasised, it was particularly extensive. At North Richmond most of the wind damage occurred above the 10 foot level, this part being most exposed to wind and having been covered with water for the shortest period. It is obvious that, if a tank be kept full, wind damage will be confined to the area above the water line, where it will be of little consequence so far as seepage losses are concerned. This is not feasible, however, in a normal farm dam, which must fluctuate in water level if it is operated efficiently, and which must be expected to be empty, or nearly so, for at least part of each year. At Richmond, for example, the conditions of operation are such that in the spring and summer months the tank is emptied at about fortnightly intervals. In normal circumstances, therefore, the water in a dam cannot be relied upon to give significant protection from wind damage.

3.3 Weathering and other damage

Subsequent to the destruction of the North Richmond liner samples were removed from it and tested in the laboratory to determine the effects of weathering and wind damage.

TABLE 1 - COMPARATIVE

PHYSICAL PROPERTIES OF NEW AND EXPOSED POLYTHENE

Test	New material 0.004 in.	Horrex material 0.004 in
Ultimate tensile strength	1850 p.s.i.	1830 p.s.i.
Percentage elongation at failure	220%	120%
B.S. Tear Strength	394lb/in	434lb/in
Elmendorf tear resistance	666 gms	310 gms.
Bursting Pressure	1.13 kg/cm^2	0.82 kg/cm^2

The significant changes are the reduction in elongation and the reduced bursting strength and Elmendorf tear resistance. These effects were the result of wind-induced working of the film. The stretching to which the Horrex film had been subjected caused plastic deformation, and so reduced the laboratory elongation figure. The weakened bursting resistance is due to fatigue cracking, the test samples all failing upon the opening of small stress cracks not present in the new material.

There was no significant change in physical properties which could be attributed to ultra-violet oxidation, nor was there any visual observation of such change during the life of the liner. There is little doubt that the use of black polythene had effectively controlled UV oxidation, at least over the short period for which the liner was exposed. At the same time, because of the way in which it

There was no appreciable evidence of piercing of the membrane from underlying stones or of damage from birds or animals. One or two punctures on the northern side were attributed to trampling by members of the installation team.

One noticeable feature was the peeling of the overlaps on the membrane welds. Along almost every exposed seam in the membrane the upper overlap peeled off in a strip about 1½ inches wide, presumably as a result of wind flapping. The manner of this peeling suggested that the welding process had produced a weakening of the membrane material immediately adjacent to the fused section. As discussed below, subsequent testing of weld samples confirmed this supposition.

3.4 The Destruction of the Liner

The Richmond liner was destroyed at about 1 p.m. on 11th October, 1958. October 11th, was a day of storms and strong squalls in the Richmond area, and Horrex reported that very strong westerly gusts occurred during the late morning and early afternoon. No wind velocity measurements are available; the Meteorological Officer at Richmond Aerodrome, 4 miles south-east of the damsite, was off duty on this day and no wind observations were made. In Sydney the Weather Bureau reported only light to moderate north west winds, with occasional gusts to 37 knots. On the following Saturday, however, a very strong squall with gusts up to 65 knots struck Sydney Harbour and caused considerable damage to small craft. It seems likely that the winds in Richmond on October 11th. were similar to those which occurred in Sydney a week later, and the velocity of the gusts which tore the liner almost certainly exceeded 50 m.p.h.

A general view of the damaged membrane is shown in Figure 5. A sketch plan is shown in Figure 10. Figures 6 and 11 show close-ups of damaged sections of the liner. The following points should be noted from the Figures -

1. The membrane failed by tearing along welded seams which were oriented approximately at right angles to the direction of the destructive wind.

2. The torn seams pass at their lowest points along the water level prevailing at the time of the failure.

From the site inspection made on October 14th and from discussions with Horrex the mode of failure seems clear. Figure 12 shows the probable failure process in diagrammatic form. It is considered that it took place as follows:-

Strong gusty winds blowing from west to east across the tank caused the whole of the eastern portion to billow. The stretching which had taken place in the previous four months permitted the liner on this side to form a large billow or "blister". The aerodynamics of the site are such that a "blister" of this type was self-supporting, its curved upper surface producing lift and so tending to cause further billowing. The effect of this aerodynamic lift was to set up considerable tensile stresses in the membrane itself. Because of the anchoring effect of the water in the lower part of the dam, and the sandbags submerged here, the tension stress was presumably a maximum along the approximate line of the lowest exposed seam. Subsequent laboratory tests have shown that the welding process produces a line of weakness immediately adjacent to the seam, and the membrane therefore split along the seam subjected to the maximum tension stress. Once part of this seam had failed, tearing along its full length followed, and this permitting the full force of the westerly wind to lift the membrane from the underside, ballooned the whole eastern section of the liner and tore it away around the line of the anchor trench.

The western part of the liner had not been subjected to the same amount of wind attack as the eastern portion, and extensive stretching had not been observed in the months prior to October 11th. The removal of the eastern section, however, produced a general slackness in remainder of the membrane and allowed a free passage of air under the western side. This, coupled with pressure fluctuations as the wind streamed over the western side of the dam, again caused lifting and billowing. Once again the tension forces set up by the billowing action caused tearing along a welded strip, and again it was the strip having least freedom of movement, i.e., the one closest to the water which gave way. In this case, however, the wind was not blowing in a direction such as to cause lifting and tearing out of the whole damaged section; instead, the eastern part of this second damaged area was blown into the water in the tank and the rest remained attached to the anchor trench. The flapping which undoubtedly followed caused secondary tearing along other seams and parts of the anchor trench, as is evidenced by the photograph.

It might be argued that the circumstances which brought this failure about were exceptional, and that a newly installed liner would have been damaged in much the same way under these conditions. If the foregoing explanation is accepted this view is, of course, not tenable. The failure was due to two contributing factors. Firstly, the stretching and holing suffered on the eastern side had brought the liner to a condition where the effects of a particularly strong squall would be such as to produce dangerous billowing. Failure to protect the liner from this stretching and holing in the first instance might be classed as faulty installation technique; it should, however, be emphasised that at the time of its installation complete covering of the membrane was not considered necessary, and it was not known or envisaged that the effects of wind damage would become apparent in so short a period of time. Secondly, the ultimate rupture of the dam took place at apparent points of weakness; i.e. along the sides of welded seams. Subsequent testing of welded seams (see "Seepage Control with Plastic Membranes," Part 5) showed that the Plastalon heat weld on new 0.004 inch material had the same tensile strength as unwelded new material. It did however have percentage elongation reduced by 6 percent and B.S. Tear Strength reduced by 4 percent as compared with unwelded material. On the other hand, the weld samples taken from the Richmond tank showed a 4% reduction in tensile strength a 19 percent reduction in elongation and a 27 percent reduction in tear strength as compared with new, unwelded material. Test figures for change in elongation and tear strength of unwelded samples from the Horrox tank showed a much greater elongation loss than the welded samples but a much smaller reduction in tear strength. It can therefore be assumed, on the basis of the figures available in the Report No. 5 referred to, that the tear strength of the welded seams in the Richmond tank became appreciably less than the tear strength of the main body of the liner, and was approximately 75 percent of the tear strength of unwelded new material. The reason for the tearing of the liner along such seams is then obvious, and it is clear that this tearing must be expected to take place along the most rigid seam, i.e., the one on the waterline where plastic deformation and creep of the material is restricted.

The reasons for this rapid reduction in the tear strength of the welds over a period of 4 months are not clear, but they can probably be attributed to fatigue as a result of wind action. There is an implication that the seams might have become very seriously weakened if the life of the liner had

To sum up, it is considered that the failure of the liner at North Richmond was due primarily to progressive wind damage over its brief life, culminating in total destruction by heavy winds when the dam was empty. Wind damage was assisted by softening, stretching and weakening of the membrane material resulting from absorption of solar heat by the black plastic material. It was manifested as fatigue cracking and holing of the membrane material and a weakening of the welded seams which has not properly been explained. Whilst the final destruction occurred under an abnormal set of circumstances, viz. a combination of strong, gusty winds, strong sunshine and empty dam, it is considered that this set of circumstances only hastened the deterioration of the liner and that it would only have been a matter of time, in more normal circumstances, before tearing of the membrane took place.

Measures for the prevention of such damage must obviously involve anchoring of the membrane and, if possible, protection from sunlight. The most obvious solution is therefore to bury it. Economic or structural i.e. slopes too steep to support cover circumstances might make this form of protection impossible. Some methods of protection are briefly discussed in the remainder of this paper.

4. CONTROL OF WIND DAMAGE ON POLYTHENE DAM LINERS.

4.1 Designing tank and liner as a unit.

From the foregoing discussion it is evident that the only certain way to protect a polythene liner from wind action is to cover it with a layer of sand or other material. A liner covered in this way is called a buried liner. Buried liners have some advantages, apart from their resistance to wind action; they are protected from ultra-violet oxidation and sunlight softening, liner movement is restricted, thus preventing the development of localised areas of high stress, and possible damage from birds or animals is minimised. On the other hand they have the disadvantage of high cost, and the placing of the cover material may cause damage to the membrane, particularly if it is of polythene. Furthermore if punctures or holes develop in buried liners they may be extremely difficult to locate and repair. The decision as to whether a buried liner is feasible depends upon the economics of the particular

possible. It would, appear, however, that long life for polythene liners can be expected only when the liner is covered.

In order to maintain a stable cover on a polythene liner the side slopes of the dam or tank should be made flatter than is normally considered necessary. It is desirable that this point be considered in designing a tank for which a polythene liner is proposed. Some comments on the stability of cover materials are given in the next section.

As well as the necessity for flatter slopes than usual, tanks lined with plastic membranes, whether buried or exposed, should have such a shape as to reduce possible folding or wrinkling to a minimum. Rectangular tanks have the disadvantage that a large fold occurs in each corner, and this may lead to damage during the covering operation in buried liners, or to wind flapping and fatigue in exposed liners. The most suitable shape of tank for a polythene liner is a circular tank, which enables the membrane to fit with a minimum of wrinkling. The fabrication of a circular liner presents no difficulties, and the Richmond liner was in fact made in this way.

It is therefore essential that a lined reservoir be designed and constructed as a unit, rather than as a conventional tank with the membrane added as an afterthought. This involves, in new tanks, the use of a circular plan, sited if possible to reduce wind action, and the use of batters flat enough to support a stable cover if the membrane is to be buried. In the lining of existing tanks it would seem to be desirable that a certain amount of reshaping and slope flattening be carried out if good liner performance is to be expected.

5.2 Buried Liners

Research to determine the best cover material for buried liners and the slopes and installation techniques to be used has been the subject of research at the University of New South Wales. The results of this research are reported in subsequent parts in this series, and particularly in Part 6, "Fabrication and Installation of Plastic Dam Liners". Brief details only are given here.

Lauritzen, in his early studies in Utah, recommended that buried liners be covered with sand or soil in a layer of three to six inches in thickness. It was also reported that a batter of 2.75 to 1 was flat enough to ensure the stability of a sand layer on Polythene.

Research at the University of New South Wales has shown that where any wave action is to be expected sand will not remain in place on a 3 to 1 slope. Sand is not recommended for cover; tests with soil have not been carried out, but it is suggested that similar comments will apply. Furthermore, the use of topsoil would necessitate very careful soil sterilisation to prevent possible penetration of the membrane by plant roots.

It has been shown at the University of New South Wales that round river gravel will remain stable and resist wind action on slopes of 1.5 to 1 and steeper. The depth of wave scouring depends upon the steepness of the slope; for batters of 2.5 to 1 and less a three inch cover layer is ample, whilst a batter of 1.5 to 1 may require a six inch layer.

It is therefore recommended that, whenever available, river gravel is the best cover material. The spreading or placing technique best employed will depend upon the size of the tank. The ideal procedure is to place the gravel from a movable chute in such a way that the fall from the end of the chute to the membrane material does not exceed 12 inches. It is preferable that this be done whilst the tank is filling, so that the cushioning effect of the water helps to prevent liner damage. Where this is not possible a very thin layer of sand might be used; the layer should be just thick enough to prevent damage to the film but not so thick that it will promote instability of the covering gravel. It can be expected to wash into the floor of the tank when wave action commences.

In small tanks placing by hand might be feasible. The use of concrete buckets of draglines may be possible in large tanks and reservoirs. In all cases the cover material should be placed from the bottom up to promote stability of the gravel layer.

4.3 Exposed Liners

Exposed liners cannot be expected to give a long life in windy locations. There may be situations in which

the subject of research at the University of New South Wales; some results are reported in later parts of this series.

One important way in which wind damage can be reduced is to protect the damsite from wind action. Skme plastic liners used in orchards where strong wind forces cannot develop have been reasonably free from wind damage. The siting of the dam to take advantage of natural windbreaks, or the growing of trees for this purpose, can be expected to reduce wind damage to some extent.

The use of thicker gauges of polythene may reduce wind fatigue. It might, however, be more economical to bury the membrane than to use a heavier material. In some situations it might be feasible to use a heavy material above the normal waterline, where wind damage is most severe, and to take steps to ensure that the dam becomes completely empty as rarely as possible.

A number of anchoring devices such as anchor spikes, sandbags, polythene pillows etc. have been suggested from time to time. The softening and stretching produced by sunlight, however, may permit extensive liner movement between such anchors and lead to rapid fatigue failure which may in fact be aggregavated by the anchoring devices themselves.

The only satisfactory device for reducing wind damage on exposed liners would appear to be a mesh covering such as wire netting or camouflage net. Such covers might, however, cause serious abrasion and lead to holing of the plastic material.

A different approach, which is still under investigation, is to construct a wind-operated evacuation system which creates a suction under the membrane and causes it to hug the ground surface. Some success has been obtained overseas with such a device, and trials are now being conducted at the University of New South Wales.

At the time of writing, however, no really satisfactory way of controlling wind action on exposed liners has been fully tested, and such liners should therefore be used with caution in windy areas. The use of wind breaks, careful dam siting and constant maintenance are essential to the success of the liner under such conditions.

5. CONCLUSIONS

Experiences with an exposed polythene dam liner at North Richmond, N.S.W., have emphasised the possible destructive effects of wind action on thin polythene memoranes.

Wind attack is a cumulative process which may culminate in extensive holing or complete rupture of a thin plastic membrane. The initial effects of wind are stretching billowing of the plastic film, which may be aggrevated by the high-temperature softening which results from exposure of black polythene film to hot sunlight. The secondary effects of fatigue and abrasion holing develop through the flapping and rapid vibration induced by excessive stretching and billowing. If allowed to continue, these secondary effects may so weaken a liner that extensive holing and tearing must follow.

Under strong wind conditions, excessive billowing may induce tension stresses in a membrane which are sufficient to cause tearing and rupture, particularly if the material has been weaked by fatigue and abrasion.

The best method of preventing wind damage is to bury the membrane under a cover of round gravel. Possible techniques for reducing wind damage on exposed liners have been suggested, but it is considered that until these methods have been proven in the field some alternative method of seepage control to the use of an exposed polythene liner is to be preferred in hot windy locations. Further research into methods for covering plastic membranes and for controlling wind action on exposed liners is in progress at the University of New South Wales.

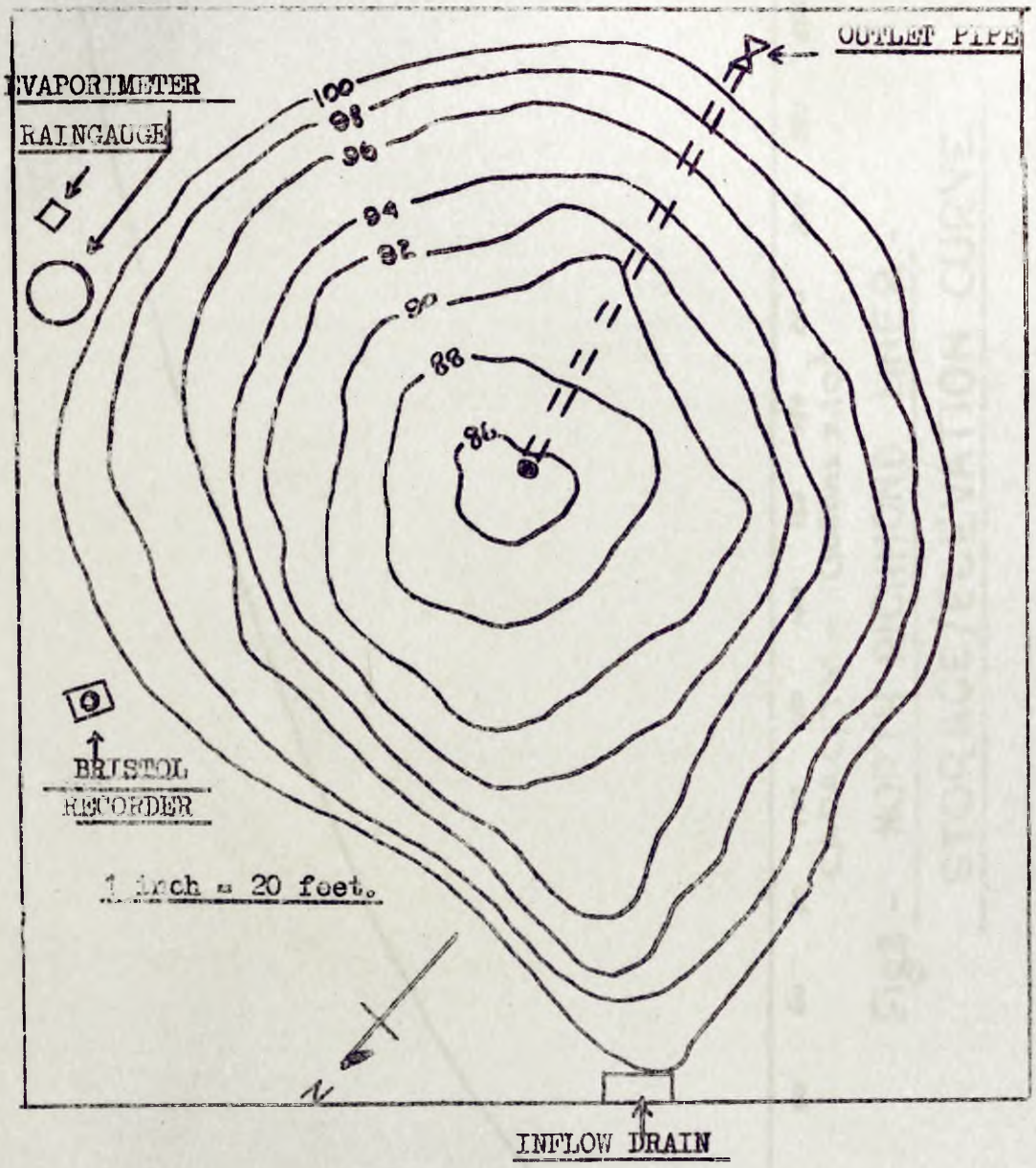


FIG. 1: NORTH RICHMOND LINER—

CONTOUR SURVEY OF TANK.

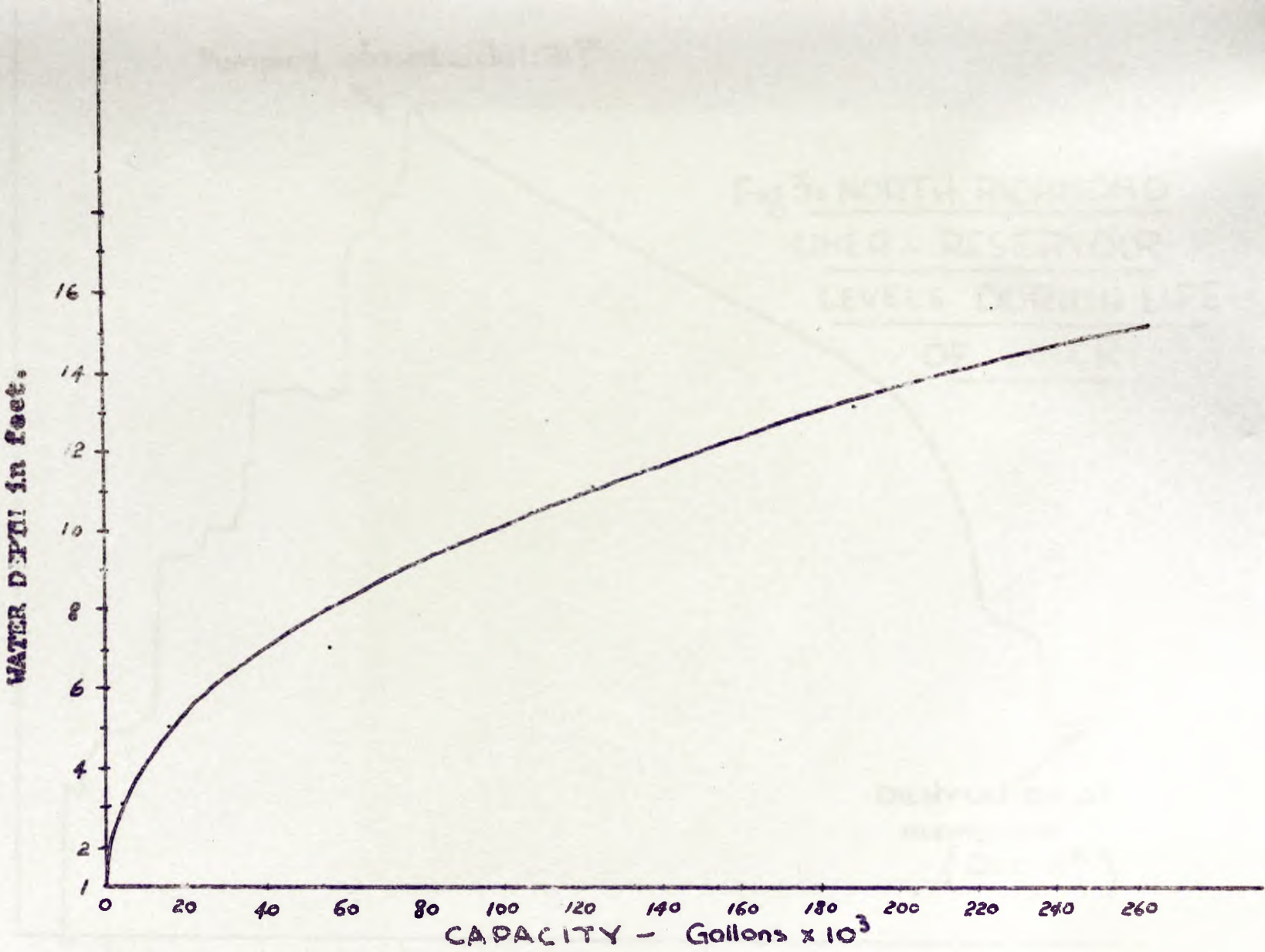


Fig2 - NORTH RICHMOND LINER - STORAGE/ELEVATION CURVE.

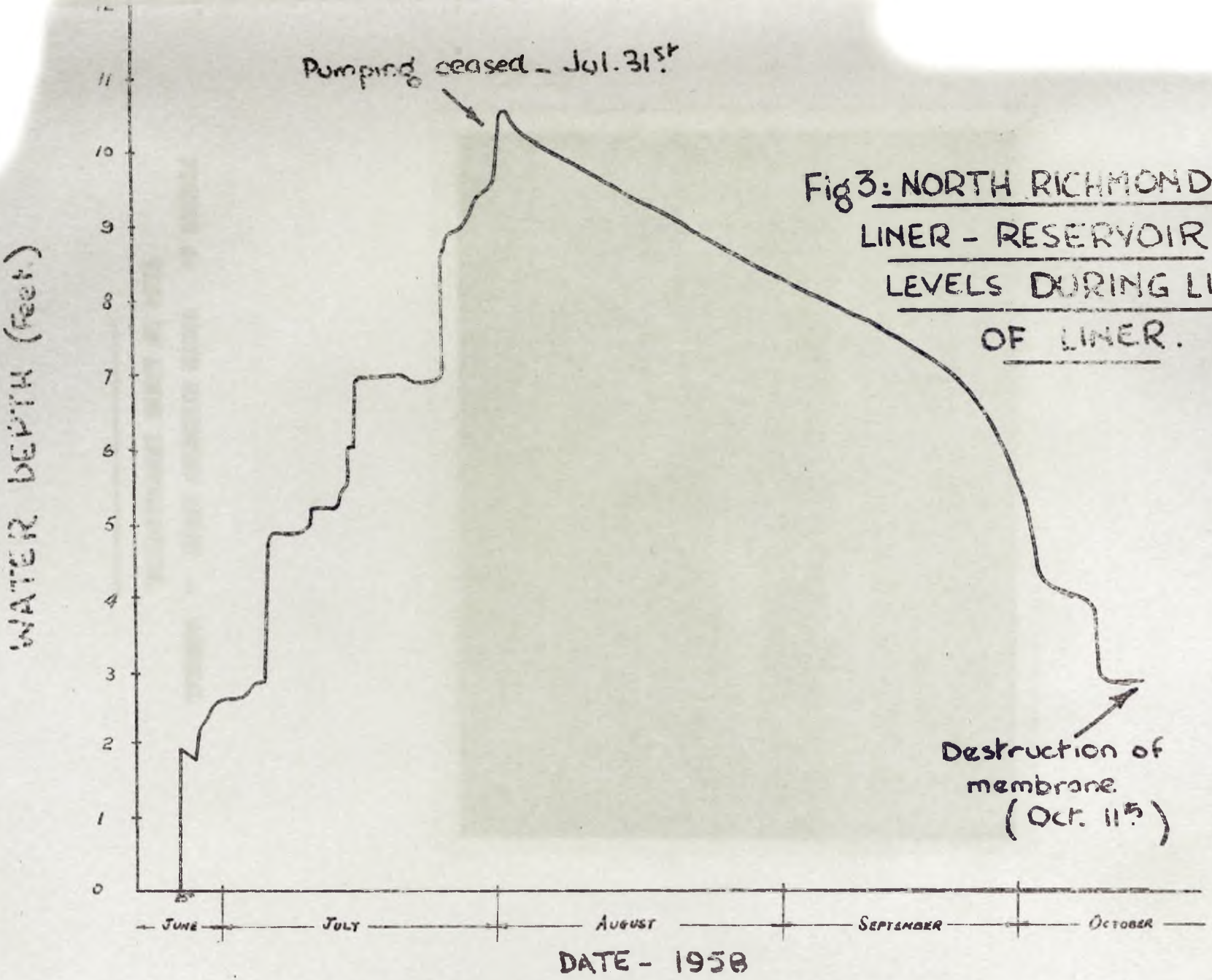


Fig 3: NORTH RICHMOND LINER - RESERVOIR LEVELS DURING LIFE OF LINER.

FIGURE 4: NORTH RICHMOND LINER - GENERAL VIEW OF LINER INSTALLATION.

FIGURE 5. NORTH RICHMOND LINER - GENERAL VIEW AFTER FAILURE OF MEMBRANE.

FIGURE 6: NORTH RICHMOND LYSIMETER -- CLOSE-UP OF RUPTURED MEMBRANE ON EASTERN SIDE.

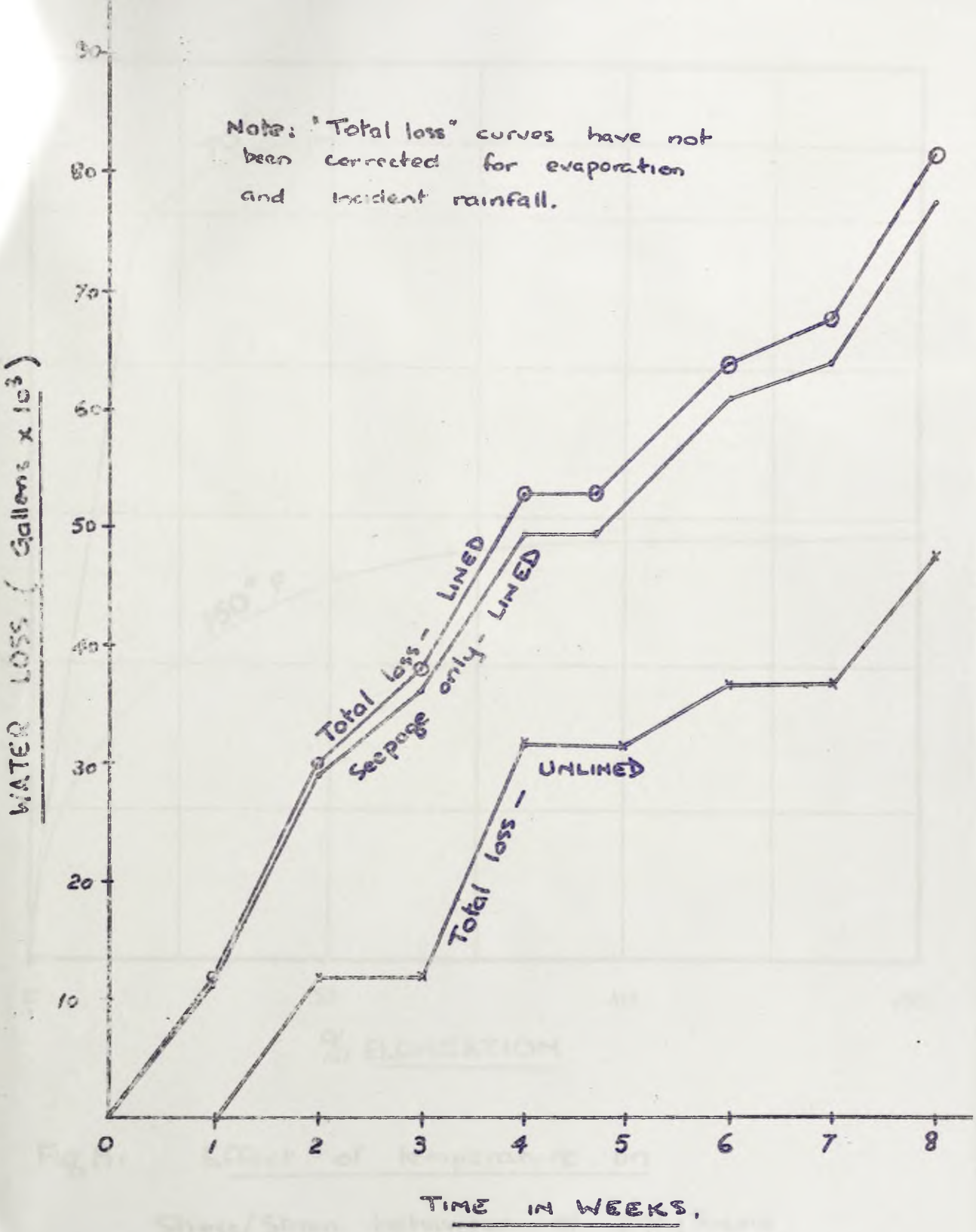


Fig 7: MASS CURVES OF SEEPAGE LOSS - NORTH RICHMOND LINER.

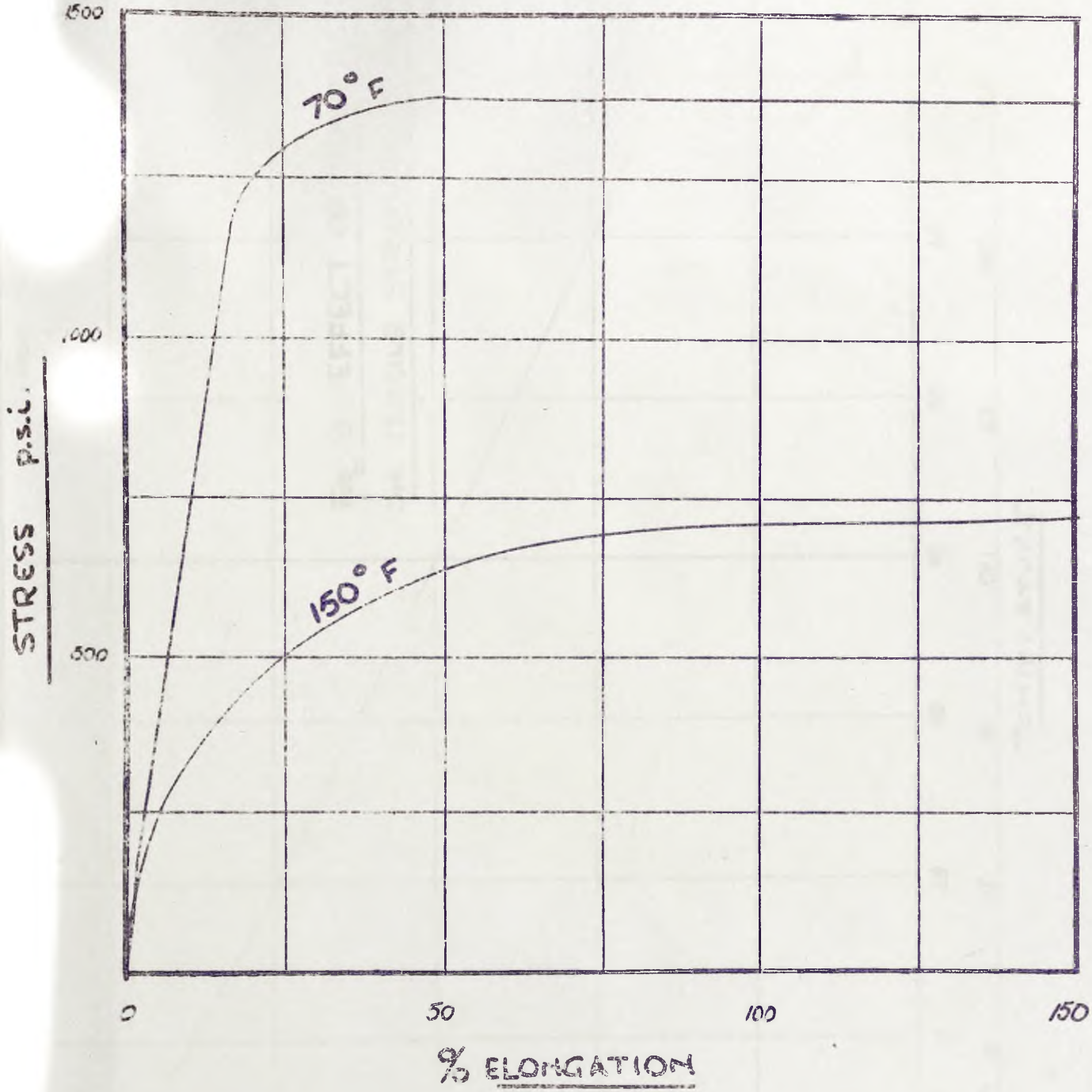


Fig 8: Effect of temperature on Stress/Strain behaviour of polythene

(Modified from "Alkathene" - I.C.I. Ltd.)

(From Raff & Allison p. 340)

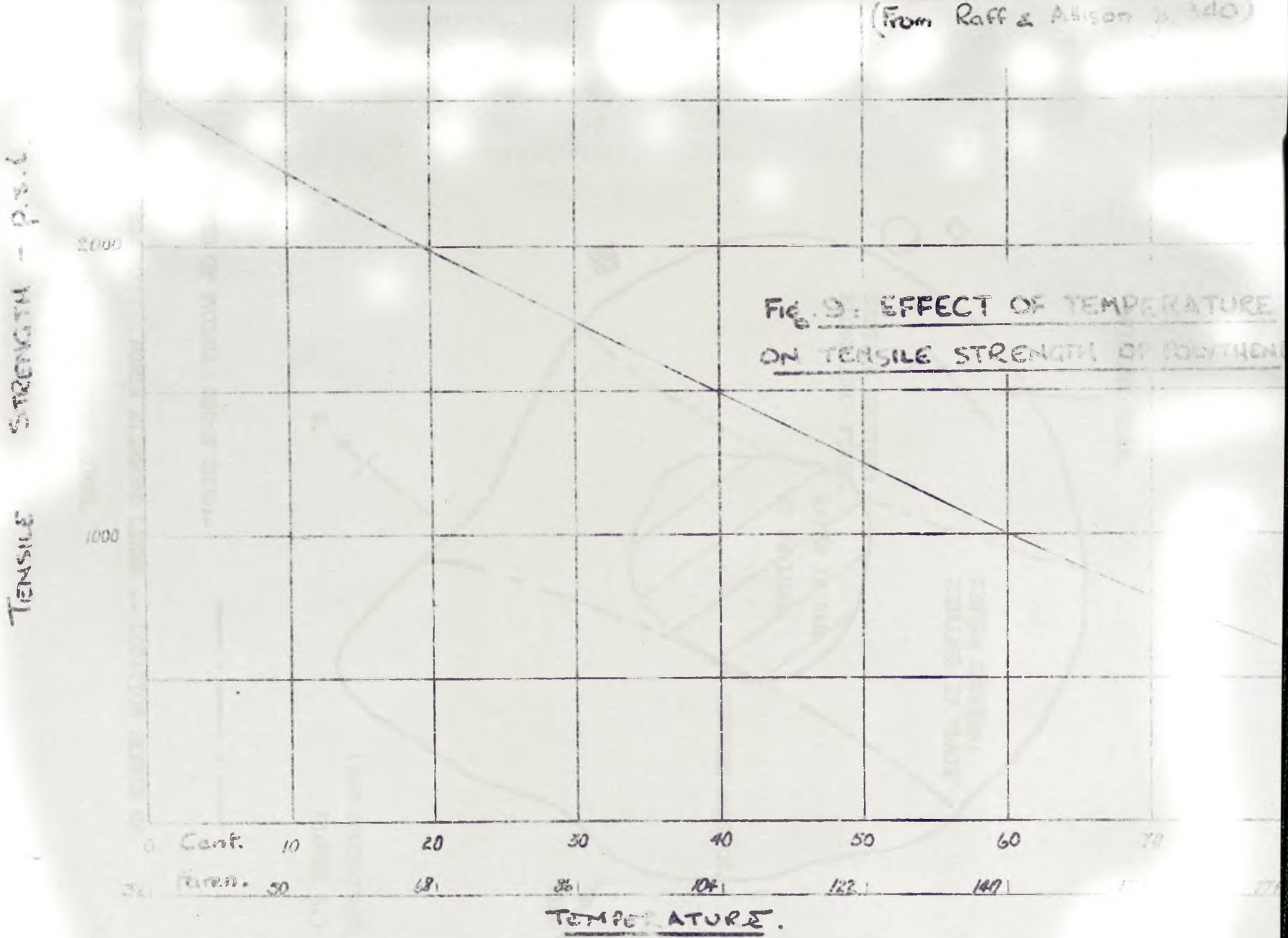
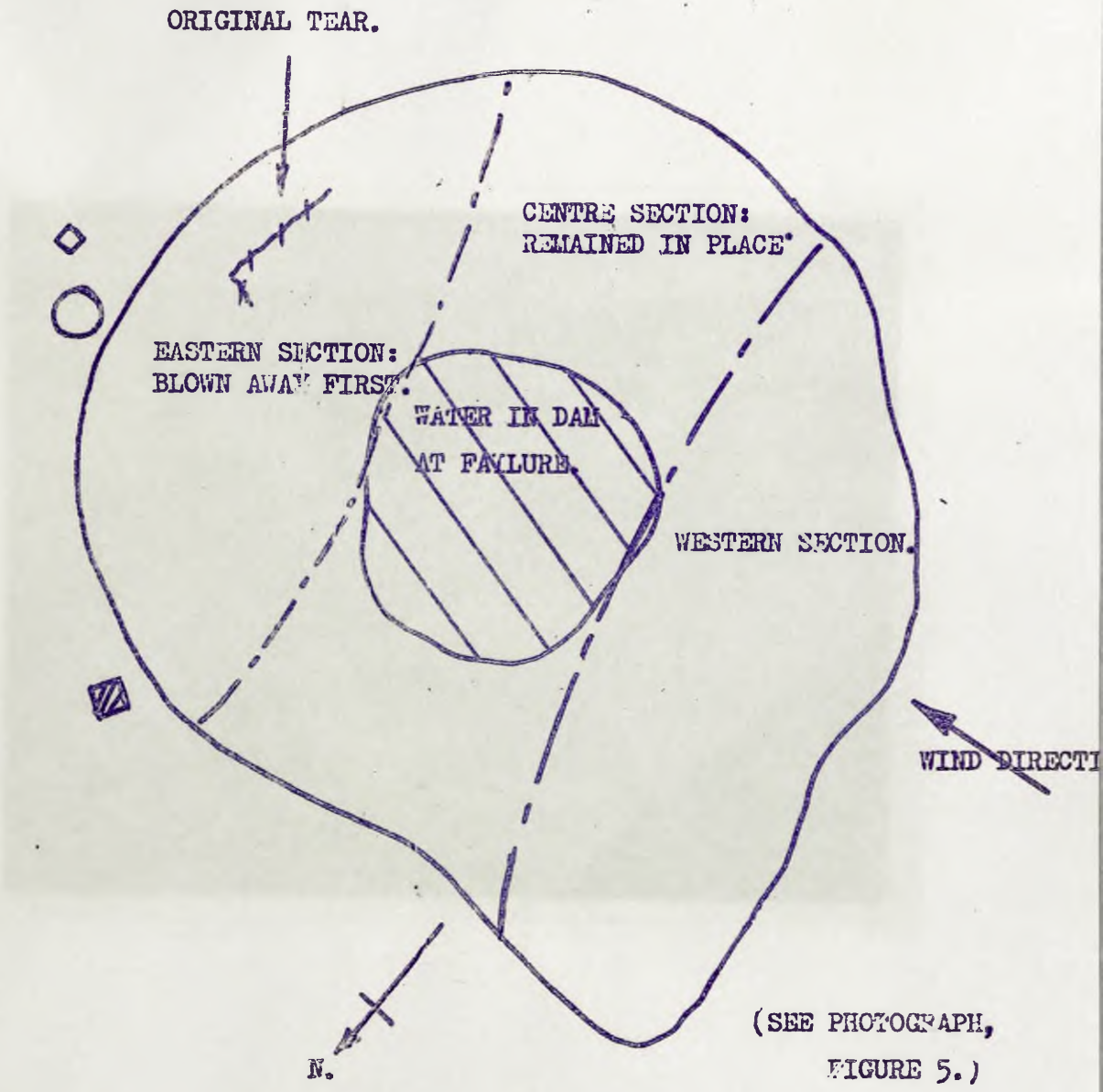


FIG. 9: EFFECT OF TEMPERATURE ON TENSILE STRENGTH OF POLYTHENE

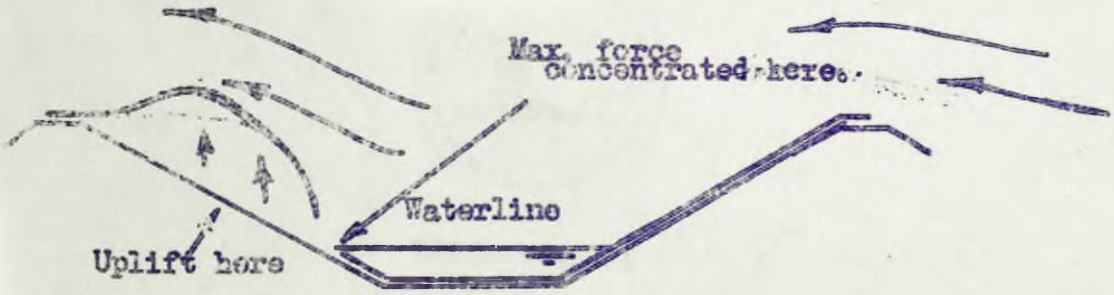


LINES OF FAILURE SHOWN THUS:-

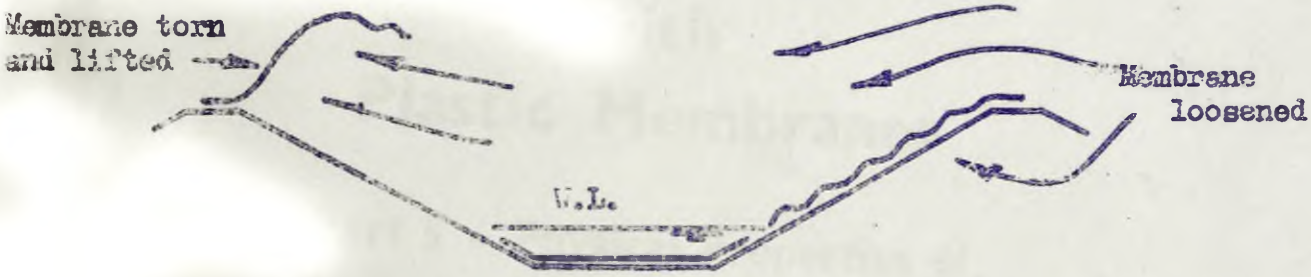
FIG: 10 NORTH RICHMOND LINER -- LOCATION SKETCH OF RUPTURED LINER.

FIGURE 9: NORTH EXCHEQUER LINER - CLOSE-UP OF RUPTURED MEMBRANE ON WEST SIDE.

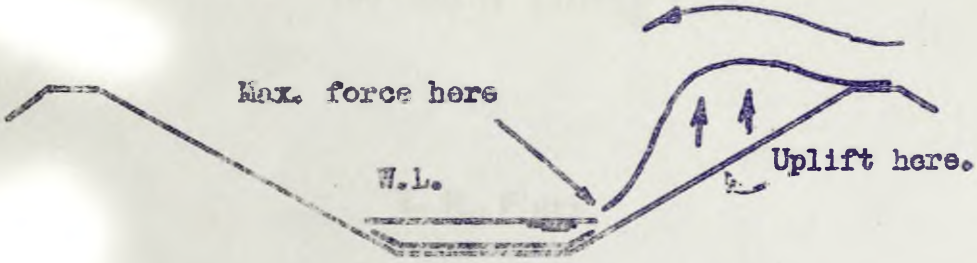
1. Wind flow pattern - westerly wind.



2. First stage of failure - membrane billowing on eastern side.



3. Second stage of failure - eastern part of membrane blown away, western part loosened.



4. Third stage of failure - western part of membrane ruptured.

FIGURE 12: THE NORTH RICHMOND LINER - MODE OF FAILURE.