Methods of creating low cost waterproof membranes for use in the construction of rainwater catchment and storage systems

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FEBRUARY 1975

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Note: All prices quoted have been converted to U.S. dollars at the rate of exchange applicable at the time of original publication. The original currency quoted is included in brackets.

SUMMARY

This publication presents the basic methods of construction of low cost waterproof membranes which are to be used to line rainwater catchment areas or water storages. The merits and limitations of each method are discussed briefly. Methods presented include the compaction of appropriate soils, the addition of chemicals to soils to improve their stability and their capacity to repel water, the use of synthetic rubber, polyethylene and poly-vinyl-chloride (PVC) membranes, the use of various types of bitumen membranes, the use of gunite, the use of an expoxy resin and the construction of sheet metal catchments. The lime stabilisation of soils is briefly discussed. The construction of small water storage tanks suitable for collecting runoff from domestic roofs is outlined. Finally, several techniques of covering small reservoirs and of controlling evaporation from open water storages are presented.

It is intended that this publication should be a survey of existing methods and will provide sufficient information for a valid comparison to be made between the methods when they are applied to a particular project.

ACKNOWLEDGEMENTS

The information presented in this paper was collected together during a two year project in Jamaica, starting in July 1971. The author was employed by Intermediate Technology Services Ltd., who had been contracted by the Overseas Development Administration of the United Kingdom of Great Britain to supply the services of an engineer to the Jamaican Government to investigate methods of improving the rural water supplies in the high White Limestone areas of the island. The project was based in the Water Resources Division of the Ministry of Mining and Natural Resources, whose Director at that time, Mr.J.B. Williams, had formulated the request to ODA for the project. As a result of the initial investigation the author had first hand experience of building small catchments of polyethylene covered with limestone chips, aluminium foil, aluminium sheeting, bitumen and reinforced bitumen. Three small storage tanks lined with polyethylene were also built and later two of these tanks were rebuilt, one as a rock filled tank and the other to incorporate a sand filter bed. These experiments led to the construction of a 660,000 gallon capacity butyl/EPDM lined reservoir and a 1½ acre experimental, artificial catchment incorporating areas of aluminium sheet, aluminium foil and chip covered polyethylene. All this work was carried out in collaboration with the Agricultural Division of Alcan Jamaica Ltd. in the Alcan mining area at West Kirkvine, Manchester, Jamaica. In the execution of this

work the author was greatly assisted by Mr. Gladstone W. Morgan, Superintendent of the Agricultural Division.

Before the project ended the author also had first hand experience of the construction of a 10,000 gallon water storage tank using a PVC lined grain bin which was erected at the Cross Keys Health Centre, Manchester, Jamaica.

A report by the author covering these and other aspects of the work in Jamaica has been published. (See bibliography).

INTRODUCTION TO RAINWATER CATCHMENT AND STORAGE

The research in Jamaica has confirmed the view stated by Lauritzen (1966) that water developed by intercepting and storing precipitation with catchment liners is economical only when other sources of water are not available at reasonable cost. The cost of developing water by these means is normally only justified if it is to serve human beings or livestock. There may be some exceptions where rainwater catchment becomes viable for agricultural purposes such as the establishment of a small market garden crop during periods of uncertain rainfall or, as reported by Myers, in a region of high rainfall such as Hawaii.

Hollick (1972) has listed conditions where rainwater catchment may be considered as a method of water supply.

a) Highly seasonal rainfall with the bulk of the rain falling during a wet season followed by a hot, dry season with high evaporation losses.
b) High variability of rainfall between years but an absence of complete droughts.
c) Underground water scarce, highly saline or inaccessible.
d) Economic situation prevents large capital expenditure on water supplies.
e) Low natural surface run off due to ground conditions.

The United States Water Conservation Laboratory in Arizona has listed the desired characteristics of an artificial catchment. They are:

1) Run off must be non-toxic.
2) Surface should be smooth and impermeable.
3) The surface should have a high resistance to weathering and have no internal chemical or physical deterioration.
4) The surface need not have great physical strength but should be able to withstand hail, intense rain, wind, occasional animals, moderate water flow, plant growth, insects, birds and burrowing animals.
5) The treatment should be inexpensive on an annual cost basis. Site preparation and construction costs should be as low as possible.
6) Maintenance requirements should be simple and cheap.

In an effort to satisfy these conditions researchers have turned to materials which are cheap, easily installed and require a minimum of specialised equipment in their installation. In ascending order of cost of the material alone, bitumen, polyethylene, poly-vinyl-chloride (PVC), and synthetic rubber have all been used to construct rainwater catchments and water storages. The bitumen when used as a buried membrane has a thickness of ¼ inch, synthetic rubber may be as thick as 1/16 inch and polyethylene and PVC have both been used as 1/100 inch thick membranes. Thus it must be appreciated that all the materials discussed in this publication have little or no structural strength of their own and depend on the design and construction of the subgrades for their structural stability. In addition, although the materials may in themselves be reasonably tough, they are used in thicknesses which make them liable to accidental mechanical damage or vandalism. The American Society for Agricultural Engineers (1970) recommends that all systems using flexible membrane linings are designed so that they will not fail structurally if built without a lining, thereby ensuring their stability in the event of the lining being punctured. Nearly all the membranes are subject to puncture by vegetation growing underneath the lining. A sensible precaution is the use of a residual soil sterilant on the subgrade unless it is certain that the exclusion of light by the membrane will prevent all growth. A few plants such as nut sedge (Cyperus rotundus), reported by Myers et al. (1970), will resist this treatment and must be killed or removed before laying the membrane.

The use of low cost membranes does not affect the normal strucural requirements of water collecting and retaining structures. They must comply with all the legal requirements and good design practice. In particular an adequate spillway must be designed to handle peak flows and to prevent overtopping any of the water storage retaining structure. Adequate provision must also be made where it is felt that ground water levels will interfere with the system. Ground water levels are often seasonal and may be dependent on local conditions such as well pumping. Drains must be installed under a membrane where ground water is thought to be a problem.

Hollick (1972) in considering the problems of rainwater catchment on farms in Western Australia where there is only 12 to 18 inches of rainfall annually has concluded that satisfactory treatments for completely sealing the catchment surface are too expensive for providing stock water and adds that it is unlikely that a dramatically cheaper method will be found. However he believes that for stock water purposes, catchments of smooth and compacted soil which reduce the natural infiltration rate of the soil are feasible. Chemical treatments and certain additives applied to the soil are also very low cost methods which can increase the run off from soil catchments.

Synthetic rubber, polyethylene, PVC, and bitumen are all oil derivatives and with the recent increase in price of crude oil it must be expected that the prices of these materials will rise. It remains to be seen whether these price increases will make the relatively highly priced synthetic rubbers no longer competitive with conventional materials such as reinforced concrete.

COMPACTED SOIL

Summary:

Clearing, smoothing and compacting suitable soils can be a very low cost method of building catchments to provide initially sediment laden water. However, large areas of low efficiency catchments may be required to satisfy demand. A clay blanket which can be prevented from drying out will provide an impermeable layer suitable for storage structures.

General:

Myers (1967) quotes experiments in Israel and the USA which indicate that if a soil is not excessively permeable significant run off can be obtained from cleared, smooth soil surfaces. In Israel, Hillel increased the run off from a 1 (vertical) in 25 (horizontal) sloping catchment on a well aggregated clay-loam soil from 5% of rainfall to 21% using this method. Myers has achieved increases from 20% of rainfall to 35% on a similarly sloping sandy loam soil. He concludes that when erosion hazards are not excessive and when large areas of low cost land are available, smoothing and compaction of the soil may be the most economical method of water harvesting.

The requirements of a soil which will respond effectively to this treatment have been given by Renfro

(3). The soil must have a wide range of particle sizes, from small gravel or coarse sand to fine sand with 10% or more of clay and silt.

Cluff (1972a) recommends this type of catchment if the soil is easily compacted and if sediment laden water will be acceptable. He gives a cost of between US $0.03 and US $0.05 per square yard for the treatment. One advantage of this type of catchment is that it will withstand the passage of vehicles.

In Australia the roaded catchment has been devised to reduce the infiltration loss to as little as possible, thus maximising run off from the smoothed and formed catchment. Hollick (1972) has tried to use a computer simulation model to determine the dimensions and layout of a given catchment which will give a maximum run off efficiency for the soil and rainfall characteristics. He reports that the catchments consist of a series of parallel cambered roads. The roads vary between 15 and 100 feet in width, depending on the soil, and the camber may be as high as 1 in 4. The run off collects in the drains between the roads, which are generally on a very shallow slope of no more than 1 in 50, and is led to the main collecting channel. This channel leads the water to the storage and if it is felt that the flow will be high enough it may be grassed to prevent erosion.

The Irrigation and Water Supply Commission, Brisbane, Australia (1970) have observed the behaviour of two such catchments. The catchments were built on a self mulching type of soil, which is not ideal, and which cannot be compacted effectively, but run off from the catchments started after only 2 inches of rain, whereas a natural catchment required 4 inches of rain before there was any run off. The catchments must be kept free of weeds and because soil sterilants proved expensive up to 5 cultivations per year of the catchment are suggested as necessary. Regrading of the roads may be necessary every three years. Sequence of construction is important and the collecting channel should be built and grassed before the remainder of the catchment is started.

The Irrigation and Water Supply Commission has also observed the behaviour of a contoured catchment where banks running across the natural slope of the catchment divert the run off into side channels which carry the water to the storage. The catchment, on a non cracking clay, reduced rainfall required before runoff commenced from 4 inches for the natural catchment to 1 inch. The maintenance of this catchment was similar to that required for the roaded catchments.

Where supplies of suitable soil are available locally a blanket of clay may be used to form an impermeable lining to a water storage. The method depends on the formation of a homogeneous sheet of clay by compacting 8 inch thick layers with a sheepsfoot roller. Renfro (3) suggests that the soil used should have a wide range of particle sizes from small gravel or coarse sand to fine sand with silt and clay making up about 20% of the weight. The compacted blanket should not be less than 8 inches thick for a head of water up to 10 feet. The Ministry of Agriculture, Fisheries and Food (1967) specify that the soil should have enough clay size particles to prevent seepage but not so much that on drying out the blanket will shrink and crack. The clay blanket must be protected with 12 to 18 inches of gravel or sand which should prevent it from drying out.

CHEMICAL TREATMENTS AND ADDITIVES TO THE SOIL

Summary:

Three types of chemical treatment have been used to increase run off from suitable soils. In general these treatments have short lives due to the erosion of the treated surface. Expansive soils which crack on drying are not suitable for this treatment.

Some chemicals when sprayed on to a soil and allowed to dry will increase the contact angle between the soil particles and any water on them to such an extent that infiltration of the water is reduced or stopped unless an external force is applied. Such treated soils have been termed hydrophobic.

A second group of chemicals when sprayed on to or mixed with a soil cause any clay in the soil to disperse or swell and partially seal the soil pores. These chemicals are referred to as dispersing agents.

Other chemicals have been used to increase the strength, the resistance to weathering and the resistance to wind or water erosion of soils. Soil stabilisation seeks to improve all the properties of the soil rather than concentrating on improving the run off characteristics only.

Bentonite, which swells to at least ten times its dry volume when fully saturated, has been used to form impermeable blankets for use in water storages. Sodium polyphosphate and sodium chloride have also been used to make impermeable blankets for water storage with suitable soils.

General:

Hydrophobic soils:

Myers et al. (1969) have experimented with several treatments, all of which produce hydrophobic soil surfaces which are subject to erosion. The chemical resulting in the most effective treatment is sodium methyl silanolate. This chemical is soluble in tapwater and when a solution is sprayed on a soil and allowed to dry it reacts with calcium or magnesium in the soil to form an inert hydrophobic resin which is not biodegradable and is stable at temperatures up to 200 degrees F. A 50 feet x 50 feet plot of sandy loam with a slope of 1 in 20, cleared of vegetation and smoothed, was treated with a 3% solution at a rate of 500 lb of chemical per acre in an effort to obtain a 0.4 inch thick layer of hydrophobic soil. In the first five months after treatment,run off was 94% of rainfall, falling to 76% over the following twelve months. Erosion of the surface took place although the underlying soil remained water repellent. The cost of the chemical was given as US $0.05 per square yard. Myers recommends that this performance be improved by mixing a suitable soil stabiliser with the sodium methyl silanolate and applying both in a single solution as a fine spray at a rate which is less than the infiltration rate of the untreated soil. This will ensure an even distribution of the chemicals and the stabiliser should reduce erosion.

Other chemicals that have been tried and found to have serious drawbacks are:-

Sodium rosinate. The chemical must be dissolved in distilled water and is said to be an effective treatment. However it is reported that the chemical deteriorates in storage.

Dialkyl quaternary ammonium chloride. The chemical is sprayed as a suspension in distilled water. Only the surface of the treated soil is water repellent and the surface is easily eroded.

Metallic soaps applied with salts. The best treatment was achieved by spraying the soil with a solution in distilled water of aluminium chloride and the soil was allowed to dry before a solution in distilled water of potassium stearate was applied. This double application produces a moderately hydrophobic soil with some resistance to erosion but the double application is considered a disadvantage.

Fatty amine acetate. Solutions in tap water have made a sandy loam soil highly water repellent. However when heated above 140 degrees F. the chemical deteriorates. This temperature is within the likely range of soil temperatures and thus the treatment cannot be considered effective.

Dispersing agents:

Myers (1967) reports that both a clay loam and a sandy loam have produced 70% of rainfall as runoff over a short period, after treatment with a 10% solution of sodium carbonate applied at a rate of 45kg. per hectare. The salt was nearly all lost after one year. Cluff is reported to have obtained 10% runoff from a sandy soil using sodium chloride powder spread at a rate of 45 kg. per hectare. He reported that runoff efficiencies of between 30% and 70% may be achieved by this treatment depending on the soil type. See Cluff (1972a). Zimmerman (1966) states that in well drained soils and where the soil is rich in calcium carbonate and gypsum the effectiveness of the sodium chloride treatment is soon lost.

Renfro (3) and Burton (1962) have both described the use of sodium polyphosphate to produce an impermeable blanket for use in water storage. Renfro states that the soil to be treated should have more than 50% fine grained material of the silt and clay particle size and at least 15% should be finer than 0.002 mm. diameter. The soil must not contain more than 0.50% of soluble salts. Renfro states that the sodium polyphosphate should be finely granular with more than 95% passing a No. 30 sieve and less than 5% passing a No. 100 sieve. The chemical is spread at a rate of 0.05 to 0.10 lb. per square foot and mixed well into the soil. For storing water up to 8 feet deep a 6 inch blanket is sufficient but for greater depths a 12 inch blanket compacted in two layers is recommended. The blanket must remain moist and near the waterline of the storage area it should be covered with 12 to 18 inches of gravel. Renfro states that sodium chloride applied at a rate of 0.20 to 0.33 lb. per square foot may also be used effectively in this way. Renfro states that chemical treatments will not be effective if the soil is coarse grained.

Soil stabilisers:

Morrison (1971) conducted an investigation into several petrochemical, liquid soil stabilisers. Sprayable liquid vinyl polymer has excellent properties for stabilising sandy soils. It produces a significant increase in the resistance of the soil to wind and water erosion. At high concentrations sprayable liquid vinyl polymer has been tested for the control of seepage on highly compacted subsoils. However a 10% mixture strength is adequate for stabilisation only and the petrochemical costs between US $0.09 and US $0.18 per square yard, depending on the mixture strength.

Liquid bitumen prime materials, which are mixed with the soil to form a 3 inch thick stabilised layer, provide excellent surfaces for resistance to water erosion. This and other bitumen applications are discussed more fully in the section on bitumen.

A water based acrylic copolymer is expensive if applied in any but low concentrations. An emulsion of a high strength synthetic rubber elastomer diluted with water applied at a rate where materials cost US $0.10 to US $0.15 per square yard was rapidly eroded indicating that the material deteriorated on outdoor exposure. An epoxised silicone formula diluted with water was found to be ineffective and costly. Petroleum resin materials have excellent soil penetrating qualities but are very slow curing which limits their suitability as soil stabilising agents because during curing the soil is prone to erosion.

Bentonite:

Bentonite is a naturally occurring clay which contains a high proportion of the mineral sodium montmorillonite. Depending on its exact make up bentonite will expand to between ten and fifteen times its dry volume when fully saturated. Two methods of using bentonite to form an impermeable blanket on which to store water have been used.

Burton (1962) and Renfro (3) report that for light sandy or loamy textured material, which will mix readily with powdered bentonite, a mixed blanket technique should be used. The bentonite is spread on the soil at a rate of between 1 and 3 lbs. per square foot and is then mixed thoroughly into the top 4 or 6 inches of the soil. This layer is then compacted. Laporte Industries Ltd., manufacturers of bentonite, suggest that, when used on open gravel, sand at a rate of 2 lbs. per square foot should also be mixed into the blanket. When wetted the bentonite swells and seals the pores in the soil, thus preventing seepage. The swelling of bentonite is a reversible process and therefore the blanket must be prevented from drying out. If it is expected that the water level in the storage will fluctuate the mixed blanket must be covered with at least 6 inches of gravel, sand or soil. Where wide fluctuations are expected Renfro suggests that this method will not be satisfactory. Burton reports that the mixed blanket method can produce a reduction in seepage of 90% or better.

The more expensive pure blanket technique must be used on heavy soils such as clay. The subsoil is smoothed and compacted and a 1 inch thick layer of bentonite is spread over it. This layer is then covered by 6 inches of gravel, sand or soil and the whole blanket is compacted. Burton claims that this method will produce savings of 95% in seepage losses. Prickett (1967) reported that the cost of the mixed blanket was US $ 0.83 to US $ 1.11 (£0.30 to £0.40) per square metre and US $1.20 per square metre for pure blankets including the soil cover. He also points out that sodium montmorillonite will undergo a base exchange in the presence of calcium carbonate and the resulting calcium montmorillonite does not retain the swelling properties of the sodium compound. He suggests therefore that bentonite should not be used on chalk soils.

Bentonite in granular form can be added to water in a storage which is known to be leaking through well defined cracks or seams. The bentonite may be drawn into the cracks and in swelling may seal them.

Zimmerman (1966) suggests that a machine to mix 10 to 25% of bentonite into sand before laying the mixture in a 2 to 4 inch thick layer will produce the most waterproof blanket. The exact percentage of bentonite depends on the form of the bentonite and will be lowest if the bentonite is finely ground and is as pure as possible. Zimmerman claims that a pure bentonite layer has proved unstable under the high water head conditions met in some reservoirs.

SYNTHETIC RUBBER

Summary:

Synthetic rubbers are manufactured from the products of oil distillation. The most common is butyl rubber althoughrecent developments have led to materials which blend butyl rubber with EPDM (ethylene propylene diene monomer). These have superior weathering properties to the unblended butyl rubber. Suitably formulated synthetic rubber sheet can be used as an exposed liner without fear of rapid deterioration. The liners are generally thicker than either polyethylene or poly vinyl chloride (PVC) liners because it is impossible to manufacture a thin sheet of synthetic rubber that is free of pinholes. Synthetic rubber liners will generally stand much more rough handling on site without damage than either of the thinner materials. Because synthetic rubber liners do not need to be protected from the elements by a soil cover they may be used to line reservoirs with steeper side slopes than those reservoirs to be lined with either polyethylene or PVC. The thicker synthetic rubber liners have been used in the construction industry in projects such as the floor of the 90 million gallon capacity Chertsey Reservoir in England as well as for relining cracked concrete water storage reservoirs. In Hawaii a nylon reinforced synthetic rubber lining has been used to waterproof the earthworks of a 1.4 billion gallon capacity storage reservoir. Reinforced synthetic rubber materials have been used in the fabrication of completely enclosed water storage tanks such as the 1½ million gallon capacity tank on Eleuthera Island in the Bahamas. Synthetic rubber liners can be fabricated easily on site by joining large sections of prefabricated liner. The liner sections are relatively easy to handle and field jointing of the liner presents no undue difficulty.

Synthetic rubber liners are expensive and approach the cost of a concrete revetment although their installation is much easier. They remain vulnerable to mechanical or malicious damage unless they are covered. If a cover material is to be used then polyethylene or PVC will provide a cheaper alternative. Their use as a catchment liner is limited by their high cost. Butyl rubber is accepted for use in potable water storage structures but other synthetic rubber materials should be checked for their acceptability to the relevant authorities before use.

General:

Unreinforced butyl/EPDM blend liners are manufactured in thicknesses between 0.030 and 0.120 inches. Most manufacturers are reluctant to recommend the use of the 0.030 thick material, claiming that it is easily damaged during installation, that there is a problem in field seaming and that the material may thin out as a result of elongation due to the stresses in the material especially on the side slopes. However several farm reservoirs in England have been built using this material and 0.030 inch thick rubber sheet is considerably less easily damaged than 0.020 inch thick PVC or 0.010 thick polyethylene, two other materials which have been used successfully in lining work. The reservoir in Jamaica was lined with a single factory fabricated 0.030 inch thick unreinforced liner and only two or three small tears were found on inspection after installation. These were easily repaired. Lauritzen (1967a),who pioneered the use of butyl rubber in water collecting and storage structures in the USA, has pointed out that one of the advantages of an exposed lining is that damage is more easily observed and repaired than in the case of a buried lining. Lauritzen has also stated that side slopes of reservoirs to be lined with butyl rubber can be as much as 1 in 1 if the liner is to be left exposed. This angle depends on the stability of the subsoil and Prickett (1967) has suggested that unless in soft rock formations the side slopes should not exceed 1 in 2. The American Society of Agricultural Engineers (1970) also recommends a maximum slope of 1 in 2 and further recommends that on long side slopes benches should be provided at intervals to minimise stress on the liner. On slopes which are longer than 20 feet they recommend that consideration should be given to using reinforced materials. Where possible, and especially where joints are being made in the field, the joints should run in a direction up and down the slope to minimise tension on joints.

Hickey (1971a) carried out a series of laboratory tests and field investigations of unreinforced and reinforced synthetic rubber sheeting. He concluded that 0.030 inch thick unreinforced sheeting was satisfactory for use as a buried or exposed lining in canals and reservoirs. There was some variation of properties of the materials but if the sheeting is properly formulated, compounded and cured the properties will be satisfactory. In cases where slopes are steep or service requirements are severe then it may be advantageous to use reinforced material. Hydrostatic puncture tests were carried out on a 0.030 inch thick material supported on a $\frac{3}{4}$ inch to $1\frac{1}{2}$ inch size rock bed. The material punctured under a pressure of 40 lbs. per square inch, which is equivalent to a 100 feet depth of water.

EPDM has a very high resistance to ozone and ultra violet light and when used in a blend with butyl rubber it produces a material which is highly waterproof, resists tearing and abrasion, rejects bacterial and fungicidal attacks and requires no routine maintenance. Uniroyal of Indiana, USA, give the life expectancy of their Royalene liner, which is a blend of butyl and EPDM, as 15 to 25 years. They claim that if permanently covered by water its life might be expected to increase to up to 75 years.

Jointing methods differ between manufacturers of sheet. The Royalene liner is joined by cleaning the splice area with solvent, applying an adhesive over a 4 to 6 inch wide strip and pushing the two sheets together. The joint is then rolled and the lap edge is finished with a bead of sealer. The liner supplied to Jamaica by Butyl Products Ltd. of Billericay, England, was joined by cleaning the splice area with solvent, applying adhesive to a 4 inch wide strip, inserting a 4 inch wide strip of uncured butyl tape and then pressing the two edges of the sheets together. Butyl rubber sheet can be heat vulcanised on site by a small machine. The American and British firms have different approaches to the supply to site of the material. Most American firms supply rolls of material measuring 200 feet by 20 feet when laid out and these are arranged to suit the particular job and then field jointed as described. The British firm will supply a factory fabricated sheet to order. This sheet is made up of narrow sheets heat vulcanised together in the factory. The sheet will tear before the joint does and the peel strength of the joint is equally satisfactory. The single sheet supplied to Jamaica was 145 feet by 140 feet and weighed nearly 2000 kilos. The weight is the only restriction on the size available.

The cost of 0.030 inch thick unreinforced butyl/EPDM material from Butyl Products Ltd. in October 1973 was US $ 1.79 (£0.73) per square yard F.O.B. London. In August 1972 Uniroyal quoted a price of US $2.61 per square yard (U.S. List price) for an unreinforced material 0.045 inches thick. A 0.030 inch thick reinforced material was quoted at US $2.79 per square yard.

Reinforced materials may use woven glass fibre, nylon or cotton as the reinforcement. Hickey (1971a) states that the properties of the nylon reinforced materials are dependent more on the characteristics of the nylon fabric used than the synthetic rubber coating. Kuehn (1971), who conducted tests on nylon reinforced materials, states that they have low shrinkage and good dimensional stability. Generally, reinforced linings have a higher water absorption than the unreinforced liners. This may reach unacceptable levels in nylon reinforced neoprene, which absorbs five times more water than nylon reinforced butyl rubber. The reinforcement reduces the flexibility and stretch capability of the sheet and it is therefore less able to respond to movements of the subsoil than is the unreinforced sheet.

Lauritzen et al. (1966) devised a small water catchment system where rain water falling on a butyl rubber sheet was channelled into a closed butyl rubber bag for storage. In general the use of synthetic rubber for catchments is too costly but Myers (1967) reports that in Hawaii, an area of high rainfall, catchments of butyl rubber covering sharp, porous cinders on slopes of up to 1 in 2.5 have been used to provide water for livestock and as supplemental irrigation for high value crops. Uplift of the sheet by the wind is countered by eliminating sharp changes in the slope of the catchment and using soil filled butyl rubber bags as weights.

There are two types of prefabricated bag which may be used in Lauritzen's system. Uniroyal offer tanks of up to 100,000 gallons capacity, which can be self supporting and lie on a prepared surface. These bags should only be used on sites where damage will not be disastrous if the bag ruptures. The bags should always be surrounded by a bund wall. Above this capacity the tank must be confined and supported by earth embankments. The 1½ million gallon capacity tank on Eleuthera Island is 110 feet square at its base, 146 feet square at its top and is supported by 12 foot high earth embankments.

The largest installation lined with synthetic rubber known to the author is the 1.4 billion gallon capacity storage reservoir covering 104 acres at Kualapuu on Molokai, one of the Hawaian islands. The material used was 0.030 inch thick nylon scrim reinforced butyl rubber. 5 million square feet of material was used. The embankments are 58 feet high with a side slope of 1 in 3½. The liner was supplied in 13½ feet wide rolls which were laid and jointed by agricultural labourers after a minimal amount of training. The reservoir was completed in 1970. Water stored in the reservoir comes from natural catchments, rivers and two ground water wells.

In an attempt to use synthetic rubber linings to their best advantage while keeping costs to a minimum it has been suggested that reservoirs can be lined with a combination of materials. The cheaper linings such as PVC or polyethylene would be used for all areas that are to be permanently covered by water or a reservoir cover and synthetic rubber would be used where exposure was expected. Thus synthetic rubber is an obvious choice for lining the sides of open reservoirs or for use in floating reservoir covers but savings may be made by the imaginative use of all the materials available.

POLYETHYLENE

Summary:

Polyethylene is a thermoplastic produced by the polymerisation of ethylene gas. The sheeting produced is naturally flexible and for all work of this nature has a black pigment added to it to combat the rapid degradation of polyethylene on exposure to light. In water storage work the film is always buried or permanently covered and for use on catchments a method of covering must be devised if the material is to last longer than a year. The material can be produced in thicknesses as low as 0.001 inch although generally a thickness nearer to 0.010 inches is used. It is the cheapest of the synthetic rubber and plastic materials. It is difficult to form strong joints between polyethylene sheets but, if the liner is to be buried, perfectly watertight joints can be made using a mastic and an adhesive tape. In lining a sloping structure such as a canal or a catchment in which the water is moving it is often not necessary to form watertight joints. lapping the upstream sheet over the downstream sheet being sufficient. The economics of using polyethylene sheet often depend on the maximum width of sheeting available. In the United States 40 feet wide rolls are available while in the United Kingdom only special bulk orders can be made to exceed the standard 25 feet wide roll. Polyethylene, because it is used in such thin sheets, is relatively easily punctured. It must be laid on a smooth subgrade which

has been treated to prevent any plant growth under the sheet. If a decision is taken to bury the liner of a water storage structure then polyethylene is the cheapest prefabricated sheet material currently available. It must be handled with care but can be laid by unskilled labour to form a serviceable liner. Side slopes of water storage structures should not exceed 1 in 3 if the cover material is to remain stable. Recently sheets of chlorosulfonated polyethylene have been manufactured and these have better weathering characteristics than ordinary polyethylene. Early compounds had unacceptably high shrinkage. Reinforced chlorosulfonated polyethylene is also now available but is in the same price range as synthetic rubber of the same thickness. The properties of polyethylene sheet depend on its correct formulation and manufacture. Specifications for polyethylene sheet have been published by the American Society for Testing Materials, the British Standards Institution and various independent bodies. Polyethylene of the highest grade should be used in water collection and storage structures.

General:

Polyethylene will degrade if used as an exposed membrane. Hickey (1969) suggests that an exposed membrane may last for 3 years. In Jamaica, 0.010 thick polyethylene sheet left exposed in water storage structures had become brittle after only one year. The material used in this way is highly prone to accidental or malicious damage. Most authors recommend that if polyethylene is to be used in an open water storage reservoir then it must be covered by at least a 12 inch thick layer of free draining, well graded sand or gravel material. If this cover is to remain stable in a storage structure then side slopes should not exceed a maximum of 1 in 2¾. The recommended side slope is 1 in 3 or even 1 in 3½ although Hickey (1969) claims that some cover materials will remain stable on slopes of 1 in 2. If polyethylene is used on a catchment or as a canal lining then the maximum slopes are governed by the stability of the cover when subjected to the maximum flow velocity.

The polyethylene must be laid on a prepared surface that is free of all sharp objects and irregularities and which has been satisfactorily sterilised against plant growth. If this surface is of a sandy material then Renfro (3) and Lauritzen (1961) recommend the use of 0.008 inch thick material in a single thickness sheet. Burton (1962) suggests that 0.006 inch thick material will be satisfactory. British Visqueen Ltd., manufacturers of polyethylene in Great Britain, recommend the use of 0.010 thick material. In Jamaica, it was noted that when the polyethylene was laid over any surface roughness the passage of a person or a wheelbarrow over this area caused the polyethylene to deform causing local thinning of the sheet but no puncturing. Under these circumstances the thicker sheets are better able to accommodate such deformations. Once an initial layer of cover has been placed on the polyethylene earth moving equipment may be used to spread the material as long as a cover of 1 foot of material is maintained under the machines and the subsoil has been well compacted. The thicker material will be advantageous in this type of application.

Lauritzen (1957 and 1961) has pointed out that if it is known that an open reservoir will always have water in it then the cover material need not be placed on the floor of the reservoir because the water will provide sufficient protection for the floor. Similarly if it is known that the water will never fall below a certain level then the reservoir side slope may be constructed in two sections. The lower, water covered, slope will depend only on the stability of the subsoil and will generally be a maximum of 1 in 2. The upper slope will be a maximum of 1 in 3 to accommodate the cover material. In reservoirs which have a permanent roof cover then the steeper side slopes of 1 in 2 may be used. The use of polyethylene without a cover material depends on successful joints in the liner which may be factory heat welded to provide single liners of up to ½ acre in size according to Lauritzen (1957) or, if the liner is field jointed, then the reservoir must be filled immediately to provide the weight on the joint that is necessary at all times to make it watertight.

Polyethylene expands on heating and is best laid in cool temperatures. It must be laid with some slack to prevent introducing stresses due to the expansion or contraction of the polyethylene. Polyethylene sheet is easily caught by the wind during laying operations. It should be laid at a part of the day when winds are not expected and as it is laid out it should be weighted down either with the cover material, if this is to be used, or smooth sacks filled with earth.

Joints between polyethylene sheets are made in the field by placing a mastic tape in the lap between two sheets and sealing the top sheet edge to the lower sheet with a 4 inch wide high quality adhesive tape. This joint must be weighted down along its whole length immediately after it is made if it is to be successful. Joints on slopes should run up and down the slope to minimise the stresses on the joint.

Hickey (1969) reported that in the United States 100 foot long rolls of 0.010 inch thick polyethylene were available in 40 foot widths at a cost of US $0.18 per square yard. In May 1972 British

Visqueen supplied the same thickness of polyethylene in 100 foot long rolls 25.5 feet wide at a cost of US $ 1.38 (£0.055) per square yard ex works. Hickey (1969) has reported that buried polyethylene linings properly installed have a long life expectancy. Some buried liners examined after ten years' service are still in excellent condition.

When using polyethylene as a liner on a smooth, compacted catchment surface two problems must be overcome if the catchment is to have a prolonged life. The polyethylene must be protected from the light and the sheet must be prevented from being disturbed by the wind. Attempts to bond the polyethylene to the soil using a bitumen emulsion solve only the latter condition. Cluff at the University of Arizona has developed the gravel covered polyethylene catchment. The gravel should be spread in a layer thick enough to just provide complete cover of the polyethylene and so protect it totally from sunlight and from wind damage. The layer must also be able to resist erosion by the run off from the catchment. If gravel of 3/16 to ½ inch diameter is used in a layer thick enough to just provide total cover Cluff (1971) reports that the gravel will just begin to move at the bottom of a 200 foot long slope of 1 in 7 if the rainfall has an intensity of 10 inches per hour. Such a gravel cover will absorb the first 0.10 inch of rainfall if the catchment is dry at the start of rainfall. Cluff reports an efficiency of 75% of rainfall over a period of 5 years for such a catchment. He has devised machines to lay and cover 0.006 inch thick polyethylene and has plans for a machine that might start on a rock scattered plane surface, pick up the rocks, prepare the soil, lay the polyethylene and cover it with a layer of the crushed rock. In 1972 Cluff gave a total cost of US $0.20 to US $0.50 per square yard for laying such a catchment, see Cluff (1972a). In Jamaica the cost of hand laying a polyethylene and limestone chip catchment was US $ 0.55 (J$0.50) per square yard in February 1973. It may be cheaper in a project to build larger areas of 75% efficient catchments of this type rather than smaller areas of more expensive 100% efficient catchment to produce the same amount of water.

In an effort to increase the efficiency of the gravel covered catchment Cluff has developed a catchment system where polyethylene or woven polypropylene sheet is bonded to the soil by a sprayed bitumen compound. The sheet is then sprayed with bitumen and given a thin covering of gravel. The use of bitumen on the runoff surface means that the water may be discoloured and can only be used for stock. (This feature is more fully discussed in the section on bitumen). Cluff gives the efficiency of this type of catchment as 90% of rainfall and its cost in January 1973 was tentatively given between US $0.60 and US $1.00

per square yard. The gravel provides some protection for the bitumen seal coat which is expected to have a life of up to 15 years depending on its source. Presumably the slope and runoff velocity limitations of the gravel covered catchment would not apply to this type of construction.

Cluff has also developed a method of using polyethylene to line water storage tanks of up to 50,000 gallons net capacity (100,000 gallons gross). The storage is excavated and the surface of the excavation is compacted and smoothed. The polyethylene is laid joining the sheets with mastic and adhesive tape. Used rubber tyres are then laid side by side all over the polyethylene and the tyres are covered with sand. The tyres support the sand on the side slopes. A layer of rock is then carefully laid on top of the sand and finally the rest of the tank is filled with rock. The tyres and sand protect the liner from damage by the rock. Experience in Jamaica has shown that the side slopes can be 1 in 2 and that water can run down the slopes into the tank although there may be some local scouring. Cluff suggests that in suitable soils the side slopes can be as steep as 1 in $1\frac{1}{4}$. This tank is only suitable for areas such as Jamaica where there are abundant local supplies of rock. The water is stored in a protected state and evaporation losses are reduced. The loss for storage purposes of up to 50% of the excavation could only be justified if the water was to be stored for long periods of high evaporation. The liner of this type of tank is protected from accidental or malicious damage and the tank can be aesthetically pleasing. Water stored in this manner is claimed to be suitable for domestic use although it would seem to have a greater application as a storage of water for stock purposes in remote areas.

Ionides (1965) developed a method of using polyethylene to line water storage tanks of up to 100,000 gallons capacity. These tanks incorporate a sand filter bed through which all the water entering the storage must pass. The method is labour intensive but uses 0.002 inch thick polyethylene sheet, does not require the jointing of the polyethylene sheet, protects the waterproof membrane with a 3 inch cover of mortar, allows the use of very steep side slopes and has a low material cost. Tanks of this design have been successfully built by the Intermediate Technology Development Group Ltd. in southern Africa. The excavation is dug, generally between 6 to 8 feet deep, with side slopes that can be as much as 3 in 1 in suitable subsoils. The excavation is smoothed and then covered with a thin layer of stiff mud, which contains herbicides and insecticides if required. The polyethylene is laid directly on the mud until it covers all the excavation, adjacent sheets being overlapped by 6 inches where necessary. A second layer of mud followed by another layer of polyethylene is then placed. Thickness is given to the membrane by laying a 3 inch thick layer of sand. This sand is contained in 3 foot lengths of 0.002 inch thick, 6 inch lay flat polyethylene tubing tied at both ends. The tubes are laid side by side, end to end, until they cover the bottom and walls of the tank. Two further layers of mud and polyethylene are then laid. The final sheet of polyethylene is protected by a 3 inch thick layer of mortar. This final revetment of mortar is made from 3 foot lengths of 0.002 inch thick, 6 inch lay flat polyethylene tubing filled with a mixture of cement and sand in a 1 to 10 or even 1 to 15 mix. The cement and sand are mixed dry and fed into the tubing. The tied tube is then punctured with six or eight holes made by a piece of 8 gauge wire and is laid in water not deep enough to cover the tube. After 5 minutes the contents of the tube should be uniformly moist and the tube can be laid in the revetment. The tubes covering the walls should be pinned to one another using short lengths of 8 gauge wire. In a few days the mortar will cure to form a hard and continuous revetment. The method ensures that a minimum of water is used and the polyethylene tubing ensures that the mortar is well cured. The 6 to 8 inch membrane so formed is water tight and will serve to line a reservoir on its own. If water is to be allowed to enter the tank by running down any of the sides they must be buttressed using more of the mortar tubes to prevent damage of the membrane by the inflowing water. More mortar tubes and wire pins may be used to form 2 to 3 foot diameter pots with domed roofs which reach to within a foot of the top of the tank standing side by side to cover the area of the base of the tank. When these storage bins have cured the spaces between them and between the bins and the sides of the tank are filled with sand. The domes of the bins should be covered with a layer of polyethylene and then all the bins covered to a depth of a foot with sand. Water entering the tank must pass through the sand before percolating between the mortar rings of the bins to enter the storage area. One of the bins is provided with a well shaft through its domed roof so that the water may be extracted. Although some volume of the excavation is lost for storage this tank provides high quality filtered water. There must be adequate local supplies of mud, sand and labour for this type of tank to be successful.

Cluff (1972a) has used a wire reinforced plaster cement to provide a revetment to the polythene liner of a water storage unit. The plaster cement protects the polyethylene from light and wind damage and prevents accidental or malicious damage. Cluff claims that this type of cover can be used on side slopes of up to 2 in 1.

Zimmerman (1966) has suggested that for smaller installations where a single sheet may be used it may prove suitable to use 0.002 inch thick polyethylene as an exposed membrane and renew it every year. The membrane remains prone to accidental or malicious damage however.

Recently the use of chlorinated and chlorosulfonated polyethylene has been reported. Hickey (1969) reports that chlorinated polyethylene is only slightly affected by burial under soil. It has a superior puncture resistance to polyethylene but a lower tear resistance. Staff (1973) reports that an uncovered chlorinated polyethylene lined catchment in a forest area of the U.S. Bureau of Land Management was still giving good service after 5 years. The cost of 0.002 inches thick chlorinated polyethylene was approximately US $1.58 per square yard in January 1973. Staff suggests that if wind damage is thought to be a problem 0.030 inch thick reinforced chlorinated polyethylene might be used. This cost US $2.95 per square yard in January 1973.

Hickey (1971a) reports that preliminary short term testing on chlorosulfonated polyethylene indicates that it has better splicing and weathering properties than polyethylene. Kuehn (1971) reporting tests on chlorosulfonated polyethylene stated that some formulations had satisfactory tensile strength, elongation properties, tear strength and ozone resistance but displayed unacceptably high shrinkage.

POLYVINYL CHLORIDE (PVC)

Summary:

PVC is a thermoplastic polymer compound of atoms of carbon, hydrogen and chlorine. It is not naturally flexible and plasticisers are incorporated to give the sheet flexibility. Stabilising agents are added to prevent decomposition of the sheet as well as lubricants to help during processing and dyes and pigments for colouring. PVC has been used in water storage structures and on catchments. It has only a short life when exposed to daylight and is therefore generally used in water storage structures as a buried membrane. In this way it competes with polyethylene and although it is easier to make a good joint between two sheets of PVC and PVC has a better puncture resistance than polyethylene these advantages may not justify the higher cost of the material. PVC may be solvent, heat or electronically jointed and can be fabricated into fitting linings for metal tanks where it will be permanently covered.

Various plasticisers may be used in the manufacture of PVC sheet. A commonly used plasticiser in Great Britain is a phthalic acid ester. This meets the requirements of the British Plastics Federation for food contact applications and no hazard has been shown to exist for water stored for drinking in PVC lined structures. Properties of the plasticisers used in a particular PVC sheet should be checked to see that they conform to health requirements before the sheet is adopted for use in domestic water applications.

General:

Hickey (1969) reports that PVC sheet is susceptible to stiffening and loss of elongation on aging due to the loss of plasticiser. Used as an exposed membrane this loss of plasticiser will limit its life to only 2 or 3 years according to Lauritzen (1966). Staff (1973) has reported a four year life of a 0.008 inch thick exposed PVC membrane although he admits this is about its expected life span.

Burton (1962), Hickey (1969) and Staff (1973) have given the properties of PVC which exceed those of polyethylene. PVC is more resistant to puncture, has greater flexibility, has a higher tear resistance, can be more easily field spliced and repaired using solvent cements, and is available in much larger prefabricated single sheets. These properties allow the use of PVC on slightly rougher subgrades than those suitable for lining with polyethylene. Staff Industries Inc.,USA, offer PVC liners in widths up to 70 feet and in any length that is suitable for handling. These rolls are delivered to site concertina folded ready to be unrolled and opened out in position.

The cost of PVC lining was approximately US $0.55 per square yard for 0.010 inch thick sheet in January 1973. 0.020 inch thick sheet cost US $0.95 per square yard and 0.030 inch thick sheet cost US $1.40 per square yard. The price varies according to the total area ordered.

PVC in water storage structures is used as a buried membrane and Lauritzen (2) has reported complete seepage control for 12 years using such a system. Side slopes of open reservoirs should not exceed 1 in 3 and the subgrade will be expected to be compacted and structurally stable. The PVC liner has no structural strength but its flexibility will allow it to accommodate some settlement of the subgrade. The subgrade should be sterilised before installation of the PVC liner. PVC linings for reservoir purposes will be between 0.010 and 0.030 inches thick. They must be covered with 12 inches of soil. Staff (1973) quotes a cost of between US $0.15 and US $0.20 per square yard for placing cover material on large projects using draglines or scrapers and graders.

Cover material is not required on the floor of the reservoir as long as 1 foot of dead water is always in the reservoir bottom. Heavy equipment may be used to spread the cover material over the PVC liner as long as the equipment runs on 6 to 12 inches of cover material and the subgrade is well compacted. Staff (1973) claims that the US Bureau of Reclamation has used more buried PVC linings in their canal work over recent years than buried bitumen membranes. PVC in large sheets is easily and quickly installed without the need for specialist machinery.

Staff (1973) advocates the use of exposed PVC membranes as rainwater catchment surfaces. He has reported the use of wind driven ventilators which produce pressures to hold the lining down in winds. He argues that, even though the PVC linings will need to be replaced regularly, the method can still be economically attractive when the low initial cost, interest and amortisation are taken into account.

BITUMEN

(In this section British terminology will be used. The American equivalents are also given).

Bitumen is a solid or semi-solid product obtained from the distillation of crude oil. Straight run bitumen (asphalt cement) is produced directly by distilling off the volatile constituents of the crude oil. Catalytically blown bitumen is produced by blowing air through a soft straight run bitumen or heavy bituminous oil at a high temperature in the presence of a catalyst. Cutback bitumen is a straight run bitumen rendered liquid or semi-liquid by the addition of a volatile distillate such as kerosene. A bitumen emulsion is a suspension of finely divided globules of bitumen in water. Asphalt (asphaltic concrete) is a mix of bitumen and mineral aggregates.

Summary:

Bitumen products have been used successfully to create buried waterproof membranes in water storage structures. Methods have been developed of hand pouring or spraying the straight run or catalytically blown bitumen to form the membranes. Some reservoir liner systems have been developed which include reinforcement

of glass fibre or polypropylene fabric in the bitumen membrane. On large scale work asphalt, laid by specialised machinery, has been used to form a waterproof lining. Prefabricated bitumen panels have also been used to form waterproof reservoir linings.

Heavy and light fuel oils have been used to increase runoff from treated soil catchment areas but do not form a completely waterproof membrane. Cutback bitumen applied in one coat has also been used in this way. Methods have been devised of applying a prime coat and later a second seal coat of a bitumen emulsion or a straight run bitumen to form a completely waterproof catchment membrane. Some of these catchment membranes have included glass fibre sheet reinforcement. Bitumen products which are left exposed to the light will oxidise and water running off bitumen catchments is discoloured by these oxidation products. These products cannot be removed by simple sand filter beds and the water collected in this manner is not an entirely satisfactory source of domestic water on a small scale. However the oxidation products have not been shown to be harmful when taken by humans. Some bitumen based paints have been developed that will reduce or eliminate the oxidation of the catchments to which they have been applied.

All bitumen membranes are prone to puncture by growing vegetation and the subgrade must be thoroughly sterilised before the membrane is laid. Where bitumen is available locally the sprayed bitumen membranes provide a cheap method of water storage and collection.

Some prefabricated sheets of sandwich construction using polyethylene sheet and bitumen or polyethylene sheet-bitumen-aluminium sheet have been developed for lining concrete roofs and other permanent structures.

The bitumen membranes have little or no structural strength of their own and depend on the adequate preparation and compaction of the subgrade for structural stability. The plasticity and flexibility of the bitumen products allow them to conform to irregularities in the subgrade and slight differential settlements of the subgrade.

Bitumen emulsions have been used to seal leaking earth reservoirs and canals by pouring the emulsion into the water filled structure. The emulsion sinks to the floor of the structure and forms a waterproof membrane with the soil.

General:

When using any bitumen products to form waterproof membranes the subgrade must be structurally stable and well compacted. All organic material should be removed and the final surface should be as smooth and uniform as possible. Zimmerman (1966) points out that all fill in embankments should be spread in thin layers and each layer well compacted. Rock fill should be dropped into position and the voids filled with progressively finer material. The rock fill should be finally covered with an earth blanket. The prepared subgrade must be sterilised using a residual soil sterilant which attacks roots and seeds. The Asphalt Institute (1961) suggests the use of sodium chlorate, urea derivatives or salts of borax and arsenic. Diesel fuel containing 1½% of pentachlorophenol applied at a rate of 0.6 to 1.0 gallons per square yard has been used successfully. Most sterilants are water soluble and can be applied by spraying.

In the United States the Bureau of Reclamation conducted tests to determine the best bitumen product for use as a buried membrane, particularly in canals. The properties that are necessary are a very low temperature susceptibility, a high degree of toughness, a resistance to tearing or breaking, a high durability and a high softening point to prevent flow of the bitumen. A catalytically blown bitumen, where the catalyst is phosphorus pentoxide, was found to be best and has been used extensively in the United States. A buried bitumen membrane will gradually absorb water and the soluble constituents of the bitumen will gradually leach out leaving the membrane with a brittle crust and a spongy core. The catalytically blown bitumen minimises this phenomenon. It has a softening point of 175 to 200 degrees F. and a penetration rating of 50/60 at 77 degrees F.

The subgrade should be lightly sprinkled with water just prior to application of the bitumen. The damp surface reduces the tendency of bubbles and pinholes to form when spraying bitumen on a dusty surface. The bitumen is applied hot, preferably at a temperature of 350-400 degrees F. The bitumen distributor should be connected by hoses to hand spray bars or spray booms supported from the distributor. Slotted nozzles on full circulating type bars have given the best results. The aim of spraying is to achieve a continuous membrane with a minimum thickness of 0.20 inches. The spray nozzle should not be held too near the subgrade and the delivery pressure must be such as to avoid kicking up the subgrade and incorporating it in the membrane. If more than one pass is required then dust should be blown off the first layer so that the two layers will be well bonded. The Asphalt Institute (1961) recommends a minimum bitumen application rate of $1\frac{1}{4}$ gallons per square yard. The side slopes of reservoirs are governed by considerations of the stability of the cover material. If soil or gravel is to be used the maximum slope is 1 in 2. However if asphalt or bituminous Macadam is used the slopes may be steeper. The cover should be placed as soon as possible after the membrane has been completed. If graded sands are used to protect the membrane from the coarser cover then the material may be spread by machines travelling on a sufficient thickness of the sand. The cover material should not be pushed down the side slopes or allowed to fall down them as damage to the membrane may result. The total cover thickness is usually 12 inches. Membranes installed in this way were reported by the Bureau of Reclamation (1964) to be giving satisfactory service after 12 years and were expected to continue to do so for many years.

Zimmerman (1966) has pointed out that catalytically blown bitumen is not generally available outside the United States and he has used the universally available hot straight run bitumens of between 40/50 and 60/70 penetration grades. He claims this material is half the cost of the catalytically blown bitumen. The hot bitumen can be applied to the wetted subgrade by pouring from cans to form a uniform membrane 1/4 inch thick. Good coverage is most easily achieved by starting the pouring operation near to the foot of the side slopes and working up the slope. The bitumen should be cooled down before pouring to as low a temperature as possible but at which the bitumen can still be poured effectively. If bitumen distributors are available then the hot bitumen can be poured from a 3 to 4 inch pressure hose at the top of the embankment. The flow of bitumen should be guided by men with swabs and controlled by playing a jet of water on to the flowing bitumen. The sides of the reservoirs should be completed before the floor is poured. The floor and the sides may be covered by using a 1 inch diameter nozzle and hose which allow the operator to jet the bitumen over a short range. Once the bitumen has hardened it should be inspected for thin areas or holes which can be locally patched. The cover material should then be placed to avoid any subsequent damage or flow of the membrane. Zimmerman considers this to be the cheapest and best way of waterproofing water storages. He quotes a cost of US $0.18 to US $0.27 per square yard including subgrade preparation for this method as used in Israel. He points out that although it is possible to use less bitumen for covering a smooth surface the method is equally applicable to open, stony surfaces. He claims the method has been used successfully on porous marl and gravel formations and that it is possible to seal fissured surfaces by jetting the hot bitumen into the fissures. Reservoirs of this type have been giving good service for 15 years and have been shown to be capable of withstanding a head of 23 feet of water.

The Bureau of Reclamation reported in 1966 that it had tried to develop a machine capable of injecting a continuous bitumen layer 6 to 8 inches below a soil surface. This was for use in structures that could not be drained and it was found that a cationic bitumen emulsion gave best results. This type of treatment had not been proved and it seems probable that there will be cheaper solutions to this type of problem.

Hollick (1972) has reported the use of various formulations and combinations of heavy and light fuel oils sprayed on prepared earth catchment areas to increase runoff. The surface formed by the treatment is not completely waterproofand there is some discolouration of the runoff water. None the less it is a very cheap way of increasing runoff.

Popkin (1965) reports tests carried out to determine the effectiveness of a single pass sprayed treatment for creating rainwater catchments. Rapid or medium curing cutback bitumen was sprayed on to a cleared, levelled and prewetted soil catchment area at the rate of 40 barrels per acre. 13 to 20 barrels of water per acre were used to prewet the soil. The method is suitable only for sandy soils which contain less than 15% of expanding clay and not more than 25% of non-expanding clay size particles. A well laid catchment has a life of about 5 years although where the soil has a high expanding clay content resurfacing may be required more often. Runoff efficiencies of more than 60% of rainfall have been recorded. The success of the treatment depends on the proper penetration of the soil by the bitumen. Laboratory tests should be carried out to determine the viscosity of the bitumen which will be related to the porosity and density of the soil. When the correct grade of bitumen is used all the bitumen will only just soak into the soil after spraying. The catchment formed by this method is still porous and therefore catchment slopes must be limited to prevent erosion.

Shell Construction Service has described a double coat spray treatment to form an impermeable surface. The first application is a medium cure cutback which is allowed to cure for a few days. A second cutback such as Shelmac S 125 is then sprayed on at a rate of 1 kg. per square metre and is covered with a thin layer of ½ inch chippings to protect the seal coat. The chippings will reduce runoff slightly.

Myers et al. (1967) have described the method of creating bitumen catchments used in Western Australia. After preparation of a compacted, smoothed, sterilised and sloping catchment area a prime coat of cutback bitumen at the rate of 0.8 to 1.6 lb. per square yard is sprayed on. Once the primer has cured a bitumen emulsion is sprayed on at the same rate. The seal coat is covered with a thin layer of sand which is lightly rolled in to protect the seal coat from oxidation. Myers conducted tests on this method to determine the best application procedure. He found that prewetting the soil sometimes increased the penetration of the prime coat of cutback bitumen but on some other soils reduced and almost prevented penetration. He found that an ideal bitumen soil blanket contained about 9 to 12% bitumen distributed uniformly throughout the depth of the blanket. When sprayed bitumen is used it is only possible at best to achieve this 9% distribution in the top ½ inch of pavement. Myers suggested that an application of a polyborchlorate soil sterilant at the rate of 0.2 lb. per square yard would be sufficient in arid or semi-arid regions. The function of the prime coat of cutback bitumen is to bond the soil particles into a reasonably strong but porous pavement. The seal coat of bitumen emulsion forms a continuous waterproof membrane on top of and bonded to the prime coat. These catchments when properly installed will yield 100% of rainfall as runoff. A soil investigation should be carried out for each new installation to determine its suitability for this treatment and to determine the properties of the prime coat bitumen for optimum penetration and concentration. A total cost including site preparation was given as US $0.73 per square yard. It was expected that a new seal coat would be required every 2 to 4 years.

The Asphalt Institute has stated that a reasonable application rate for a cutback bitumen prime coat is ½ gallon per square yard, but as much bitumen as the ground will absorb should be applied. This coat will require one or two days of good weather to cure. Many bitumen emulsions may be applied cold but if bitumen distributors are available the Asphalt Institute recommends the use of catalytically blown or straight run bitumen of a low penetration grading for the seal coat. The application rate is estimated at 1 to 1½ gallons per square yard.

Myers et al. (1970a) developed a reinforced bitumen membrane which he claims is more durable than the unreinforced membrane described above. The construction technique may be used for either catchments or lining water storages. The subgrade is prepared and sterilised as usual. A tack coat of either cutback bitumen (hot) or bitumen emulsion (cold) is sprayed on the soil surface at a rate of 1/4 gallon per square yard. The reinforcement is chopped strand fibre glass matting weighing 1 oz. per square foot and is rolled out on top of the tack coat. On catchments, the strips of reinforcement are laid across the slope and each sheet overlaps the strip below it on the slope. On the slopes of water storages the strips should be laid up and down the slope. The reinforcement is then saturated with the type of bitumen selected for use as the tack coat at a rate of 1/2 to 3/4 gallons per square yard. The bitumen is left to cure until it is no longer tacky. Myers claims that emulsions will cure in 1 to 2 weeks while cutbacks take two to four weeks. When the base coat has cured a seal coat of bitumen emulsion (cold) or catalytically blown or straight run bitumen (both hot) is applied by spray at a rate of between 1/3 to 1 gallon per square yard. If this method is used for water storage reservoirs which will contain more than 10 feet of water then two seal coats should be applied. In 1971 Myers estimated the cost of such a liner at US $0.75 per square yard. This cost is largely dependent on the cost of the reinforcement and in Jamaica in 1972 the best cost of this type of lining was US $ 1.79 (J$ 1.42) per square yard, the reinforcement accounting for 60% of the cost. Myers states that the seal coat will need renewing every 5 to 10 years if it is exposed to the light. The Irrigation and Water Supply Commission of Brisbane, Australia, built two of these catchments in 1970 and have reported the importance of achieving a good bond between the soil and the reinforced membrane and of using a heavy glass fibre sheet.

Phillips Petroleum Company, USA, promote a commercial system of producing a similar reinforced bitumen membrane, mainly for use in water storage reservoirs. The reinforcement is carbon black treated polypropylene fabric unfused on one side to improve the bond with the bitumen seal coat. Rolls of the fabric, which weighs 5 oz. per square yard, come in 200 foot lengths each 15 feet wide. The fabric is joined by sewing with polyester and cotton thread. The fabric is laid out and jointed to cover the prepared subgrade area. Asbestos filled bitumen emulsion is then sprayed over the reinforcement. Other bitumen products may be used to seal the reinforcement but the application temperature of the bitumen must not exceed 200 degrees F. Crushed rock is then spread on top of the bitumen and lightly embedded. When the first application of bitumen has cured a second coat should be applied which is just sufficient to coat each rock chip. The rock chips create an abrasion resistant surface. These liners may be used for reservoirs of depths of up to 25 feet. They appear to rely only on their own weight to keep them anchored down as there is no physical bond between subgrade and liner.

The manufacturer recommends using cover material if wind uplift is thought to be a problem. The liner cost US $2.00 per square yard in 1972. This is a high price for a liner which does not appear to have any outstanding features.

Water running off exposed bitumen surfaces is often coloured by the products of the oxidation of the bitumen. Filtration through 30 inches of sand or soil will not remove these compounds but Myers et al. (1967) report that they can be removed by cationic exchange resins. The water is normally odourless and tasteless and is readily consumed by cattle. The discoloured water is believed to be harmless to humans. Myers et al. (1970b) report that bitumen derived from Venezuelan crude oil resists photo-oxidation better than bitumens derived from Californian crude oil. Discolouration of runoff from the Venezuelan derived bitumen is only 25 to 50% of the discolouration from Californian derived bitumen. Aluminised bitumen paint cuts discolouration from Californian bitumen by 70% and rubberised aluminium paint cuts it by 95%. These two paints were still experimental in 1970 but were expected to cost less than US $0.05 per square yard.

The Asphalt Institute suggests that sand or pea sized gravel spread over freshly sprayed bitumen and lightly rolled into the surface will reduce oxidation. Alternatively a solution of 1 sack of Portland cement and 7½lb. calcium chloride in 10 gallons of water may be sprayed on to a bitumen surface and dries to a near white reflective coating. Commercially produced reflective paints such as Decoralt tend to be expensive. In Jamaica the cost of Decoralt in 1973 was US $ 0.17(J$0.15) per square yard.

Asphalt, a carefully designed mix of bitumen and graded aggregate which is mixed and placed while hot, has been used extensively on large water storage structures. The blanket of asphalt is usually 3 inches thick although for smaller structures such as small reservoirs and farm ponds a 2 inch thick layer may be sufficient. The Asphalt Institute gives a minimum thickness of 1½ inches. These blankets are stable, durable, erosion resistant, can withstand the passage of vehicles and do not require any cover material. They are able to accommodate slight movements or settlements of the subgrade and are stable on slopes of 1 in 1¾ for vertical heights of up to 20 feet and on slopes of 1 in 2 for vertical heights of between 20 and 40 feet. The design of the mix and the method of placing it determine the permeability of the asphalt blanket. Densely graded aggregates and mineral fillers are used to create a voidless mix. Excellent compaction is required on site if the blanket is to be durable and not prone to cracking. Hickey (1971b) states that field compaction should be 97% of that obtained in the laboratory using the standard laboratory methods. Field compaction is usually obtained by using paving machines and steel wheel rollers which may be winched up and down the side slopes of the structure. This makes the use of asphalt more suitable for large installations where the laying and compacting machinery can be used effectively. Membranes of sandwich construction consisting of layers of asphalt of different permeabilities have been built. Such a membrane enables the designer to incorporate a stable porous layer which allows the collection of ground water and its transport to drains below the waterproof membrane. These sandwich constructions may incorporate layers of straight run bitumen and Zimmerman (1966) has suggested the use of asphalt as a cover material for buried membranes. Asphalt suffers from penetration by vegetation and subgrades should be well sterilised. Asphalt can be laid to reasonably close tolerances of thickness and permeability using the equipment described.

In structures where the waterproof lining must be laid to exact specifications of thickness and permeability the Asphalt Institute recommend the use of prefabricated bitumen panels. The panels are generally ½ inch thick and consist of two outer layers of a tough, bitumen impregnated material such as asbestos felt or fibre glass fabric with a core of a very dense mixture of bitumen and filler. The panel may be coated on both sides with hot applied bitumen. The standard panel is typically 3 to 4 feet wide and 10 feet long and panels are joined to one another either by lap joints or butt joints using hot bitumen adhesive or cold applied bitumen mastics and a bitumen joint strip. The panels are reasonably flexible and will conform to changes of angle in the subgrade. Some early panels incorporated a reinforcing mesh but the mesh reduces the flexibility and is prone to move out of the panel. These panels have proved particularly successful for relining cracked concrete reservoirs where access was limited.

Prefabricated bitumen rolls have also been used in circumstances where more flexibility and less strength and toughness are required. The rolls consist of asbestos felt or fibre glass matting saturated with bitumen and are typically 3 feet wide, 36 feet long and 3/16 inch thick. The rolls are joined using lap joints and hot applied bitumen or cold applied bitumen mastics. This type of material has also been used as a buried membrane covered by 12 inches of soil or a thinner layer of bitumen Macadam.

The U.S. Bureau of Reclamation (1963) and the Shell Construction Service (1969) have both described the use of a bitumen emulsion as a waterborne sealant for use on suitable soils. Best results are obtained if the water is not flowing. Cationic bitumen emulsion is poured into the water which is agitated to achieve as even a distribution of the bitumen as possible. The bitumen settles to the sides and bottom of the structure where it will stabilise the soil surface. The soil surface should be free of weeds and vegetation, and all loose fine material. The treatment will not be effective unless the soil is free of holes and presents a uniform surface. The bitumen does not penetrate very far into the soil but the Bureau of Reclamation reports that no erosion was observed with flow velocities of 3.6 feet per second in a section of a treated canal where the subgrade was a sandy soil. More erosion was noted due to wave action on the side slopes. The application rate was ½ gallon per square yard. Shell report a reduction of seepage by 70 to 90% using this treatment on leaking canals in Italy. They state that the treatment will have to be repeated every 3 to 4 years.

The Larutan Corporation of California market an emulsion of oil soluble resinous polymers which can be used in the same way as the bitumen emulsions. It can also be diluted and sprayed on to a soil surface but if the seal achieved by spraying is to be preserved a bitumen seal coat is required unless the surface is flooded immediately and kept constantly wet thereafter.

SHEET METAL CATCHMENTS

Summary:

Corrugated galvanised sheet steel has long been used to collect rainwater. In recent years artificial catchments have been built by laying the sheet steel directly on a prepared ground surface. In Jamaica 0.015 inch thick aluminium sheet was used to form nearly 1 acre of catchment area in this way. Aluminium foil has been used by bonding it to the soil surface with cationic bitumen emulsion. In Jamaica aluminium foil 0.003 inches thick was used to form a catchment. The foil was held down with suitable weights scattered across its surface.

General:

Galvanised steel catchments of 22 gauge material have been reported in use in the United States, Australia and Gibraltar. In Jamaica galvanised steel catchments mounted on wooden frameworks have been in use for over 20 years. The Jamaican catchments have suffered considerable damage during hurricanes but were rebuilt and have withstood tropical storms which caused some distortion but left the catchments still effective. Lauritzen (1967b) tried to reduce costs by doing away with the wooden framework and laying 22 gauge galvanised steel sheet directly on a prepared earth surface. The sheets, which had a raised trough section on each edge, were laid in a staggered pattern and joined to one another using sheet metal screws. The sheet was anchored to the ground by specially shaped edge sections screwed to the edge sheets and buried in the ground. The Irrigation and Water Supply Commission, Brisbane, Australia, reported the construction of two similar catchments in 1970. The sheets had 1½ inch upstands on each edge which were secured to adjoining sheets using "clenching tongs". The catchments were secured to logs buried underneath the sheet and also surrounding the edges of the catchment. Runoff from the catchments was 100% of rainfall. The cost was quoted as US $ 1.85(A$1.65) per square yard. Experiments were also carried out using light gauge aluminium sheet but the joints proved unsatisfactory because the wind tore them open and lifted the sheets.

In Jamaica 0.015 inch thick aluminium sheet has been used. The sheets have a raised trough section at each edge and have been laid in a staggered pattern and joined together using sheet metal screws. The catchment is anchored to aluminium sections buried under the sheet at 25 foot intervals running across the slope of the catchment as well as sections around the edges of the catchment. The cost of the sheet including the laying and jointing was US $ 1.30 (J$1.17) per square yard in 1973. The subgrade must be smooth, free of any sharp projections, sterilised and free of sudden changes in slope.

Myers (1967) reported that a catchment of 1 mm. (0.04 inch) thick aluminium foil bonded to a soil surface with cationic bitumen emulsion was showing no signs of deterioration after 5 years of exposure.

In Jamaica strips of 0.003 inch thick aluminium foil with a dimpled surface were laid on a prepared smooth soil surface and bonded to one another using a black plastic cement. The foil was weighted down with used car tyres spaced approximately one every 7 to 8 square yards. This catchment performed reasonably for a year but the joints are not strong and if opened up by the wind the weights are not sufficient to prevent the foil being lifted. The cost of the foil including laying and jointing was US $ 0.79 (J$0.71) per square yard in 1973.

GUNITE

Summary:

Gunite is a sand cement mortar which is projected at high velocity on to a surface. The force of the jet impacting on the surface compacts the mortar. Gunite is often used to repair cracked concrete structures but may be used to form the lining of a reservoir or a channel. It has an obvious application in making relatively thin catchment surfaces. Costs of gunite and unreinforced concrete are very similar. However Gunite does not require formwork, it can be carried long distances by the air pressure and the plant required is small and relatively easily transported.

General:

Gunite may be mixed and applied using small portable plant. A 21/14 concrete mixer is suitable for mixing the sand and cement which is then fed to the special nozzle where it is mixed with water and jetted to its final position. A 600 cubic foot per minute compressor will provide sufficient air pressure. The sand and cement are mixed in a ratio of 4½ to 1 by weight which, with rebound from the final surface, becomes finally 3½ to 1. A relatively dry mixture is used so that the Gunite is self-supporting and will not slough on application. The subgrade must be well compacted and prewetted but not saturated. The Gunite layer must be reinforced, usually with high tensile steel mesh reinforcement. The finished surface of the jetted Gunite will be rough but can be trowelled smooth. It is essential to cure the Gunite properly either by keeping the layer damp for at least seven days after laying or by applying a curing sealant to the Gunite immediately after it is completed. In hydraulic applications Gunite may be laid in thicknesses up to 9 inches. Zimmerman (1966) has reported that, like concrete, Gunite is prone to hairline cracking.

EPOXY RESINS

Summary:

Craig Plastics, Nottingham, England, market a product, Geophil, which is a special blend of epoxy resins. They claim that it may be used to seal porous rock strata or rocks with small cavities as well as creating waterproof seals in loose sands. Epoxy resins are expensive materials and it is difficult to imagine a job on which their extensive use would be the cheapest solution.

General:

Epoxy resins cure to form a hard, impervious skin of great strength. The resin will bond well to rock, is not attacked by chemicals and has a very low coefficient of linear expansion. However the resin is not very flexible and settlement or movement of the subgrade will probably crack the membrane. The resin is applied by spray. The possible applications include the construction of cut off walls down to impervious soil layers or the local sealing of porous rocks that outcrop in water storage or catchment areas.

LIME STABILISATION OF SOIL FOR CATCHMENTS

Summary:

Lime stabilisation and cement stabilisation of soil have been used extensively to increase the strength and reduce the plasticity of suitable soils. This has particular application in the building of roads where the strength of some soils may be increased to make them suitable subgrade material. The stabilisation also makes the soil less susceptible to the reduction in strength normally associated with increases in the moisture content of the soil. It will also reduce the shrinkage and swelling of certain soils. It is in this latter respect that this method may have an application in producing stable catchment surfaces. The method requires laboratory analyses of the soils, experiments to determine the optimum application rates of hydrated lime and the optimum moisture content for compaction as well as a considerable number of machines to apply the lime and compact the blanket and good site supervision. It is doubtful if lime stabilisation alone will produce a durable catchment surface.

General:

The Road Research Laboratory (1969) indicate that the plasticity index of the soil to be stabilised should be less than 25 and that the soil should contain a small fraction of silt or clay for the lime stabilisation to be effective. Generally a lime content greater than 4% by weight does not produce any further reduction of plasticity or increase in strength. The most uniform mixture of lime with the soil is obtained by using a single pass stabiliser or a stationary mixer. However once the soil has been brought to its optimum moisture content for compaction the lime can be spread on the surface at the desired rate and mixed into the soil using a disc harrow or plough and a grader. The mixture should be compacted with a sheepsfoot roller followed by a rubber tyred roller and finally a steel wheeled roller. The blanket must be graded as necessary during the process and must be maintained at its optimum moisture content. After construction the blanket must be cured for at least 10 days, watering the soil regularly to keep it damp. The surface so formed is strong and stable but is prone to hair line cracking. It may be further treated with bitumens to create a completely waterproof surface. This method may be attractive in areas where limestone is freely available. The limestone may be burnt in simple kilns to produce hydrated lime.

SMALL WATER STORAGE TANKS SUITABLE FOR ROOF CATCHMENT

Summary:

Tanks which are to be used to store water collected from roofs which will be used for domestic purposes should be covered and ideally should have a means of removing the water which does not involve lowering a water receptacle into the stored water. This is generally achieved by the use of a small hand or electric pump which may feed an overhead distribution tank. In order to collect water from the roof tops most of the tanks will be too low for gravity distribution of the water and may have to be partially or wholly sunk in the ground. In Jamaica, in an area where the average rainfall is approximately 65 inches per year and there is no other supply of water, it was considered that each household required a 10,000 gallon capacity tank to provide a reasonable supply of water for a family throughout the year. Tanks built completely in situ include those requiring excavation and subsequent lining with concrete blocks, steel reinforcement and plaster. The tank developed by Ionides, already described in the section on polyethylene, also comes in this category. Morton (1968) has described the construction of a reinforced mortar tank with only 3 inch thick walls which are limited to a height of 6 feet, which is also built completely in situ. Covered

grain bins are easily adapted to water storage purposes by using synthetic rubber or PVC prefabricated liners. This type of tank will require the preparation of a suitable base and the erection of the tank and liner. Prefabricated sectional pressed steel tanks and sectional reinforced plastic tanks require a levelled area of suitable bearing capacity before they can be assembled. Small prefabricated welded steel tanks and prefabricated reinforced synthetic rubber bags may be placed on prepared level surfaces. Roofs for tanks used in domestic or public situations should be rigid and capable of sustaining the weight of a human being for reasons of safety. In the next section some floating covers which could be used on small open tanks are discussed, but they will not prevent people falling in the tanks.

General:

Tanks which require up to 6 feet of excavation in soft limestone rock are commonly built by local masons in Jamaica. The excavation is lined with concrete blocks, the cavities of which are filled with concrete and may be reinforced with steel. If the tank walls extend above the ground level they will be made thicker with either a second wall of concrete blocks or suitable buttressing using locally available limestone blocks and mortar. The tank is waterproofed using a mortar of cement and marl. The lowest estimate received from a commercial building firm for the construction of a 10,000 gallon tank with a rigid roof using this technique in Jamaica was US $ 2,216 (J$ 2,000.00) in 1973.

The tank developed by Ionides has already been described in the section on polyethylene. A tank using the same construction techniques was built in Jamaica in 1973. It was estimated that the materials to build a tank of at least 2,500 gallons capacity cost US $ 332.40 (J$ 300.00). Two-thirds of this cost was the sand used in the filter bed. It is felt that where sand is available locally and the subgrade is capable of standing at steep slopes the cost of the storage tank would be substantially reduced.

Morton (1968) describes the construction of reinforced plaster tanks in southern Africa. The tanks require good rock foundations or a mesh reinforced concrete base. The walls are built up using 24 gauge corrugated galvanised steel shuttering. A complete ring of shuttering is set up on the wall foundations and wire mesh pig netting is drawn tightly around the outer face of the complete shutter and secured in place using 16 gauge wire. The main tensile reinforcement of 8 gauge wire is then wound tightly around the shutter to obtain the designed number of turns per foot depth of shuttering. In a 60,000 gallon tank of 45 feet diameter and with a 6 feet deep wall, 33 strands of reinforcement are required in the lowest foot of the wall with at least 6 strands in the bottom 2 inches. The reinforcement reduces to a nominal number of only 3 or 4 strands in the top foot of the wall. The design assumes that the wire will be stressed to 12,000 pounds per square inch. The plaster is a 1:4 cement/sand mortar. A fairly dry mix is made and the plaster is placed on the shutter covering all the wires and is pushed well into the corrugations. After 24 hours, during which time the plaster must be kept damp, the shuttering is unbolted and removed. It is then raised and fixed in position for the second lift of the wall. The process is then repeated for the second lift. At the same time the corrugations on the inside of the first lift are filled up to form a plane surface with all the reinforcement covered. The wall is finished by plastering the inside surface with a 1:3 mortar and the outside surface with the 1:4 mortar. Thus a reinforced wall of 3 to 3½ inches thickness is built. Throughout construction and for up to a month afterwards the walls should be kept damp so that they gain strength during the curing process. Morton does not report what maintenance is required or what the expected life of the tanks is. However, in areas prone to earth tremors such as Jamaica, it would not seem wise to build a tank with such thin walls. It is also likely that these walls will be prone to hairline cracking and that if the tank is allowed to dry out these cracks might soon become a source of loss due to seepage. Morton reports that the construction is simple and can be carried out by unskilled men under the supervision of a mason at low cost. The shutters may be used repeatedly. The thickness of the walls restricts their height to 6 feet but design charts exist for tanks of up to 150,000 gallons capacity with a diameter of 60 feet.

Lauritzen et al. (1969) have described the use of a galvanised steel grain bin fitted with a PVC liner to make it watertight as a water storage unit. A suitable base for the tank walls must be prepared. If the subgrade is suitable the cheapest base will be well compacted earth. The most expensive will be a mesh reinforced concrete base. The walls of the grain bin are erected on the base using dome headed bolts on the inside of the tank. When the wall is completed a length of split plastic hosing is slipped over the top edge of the wall. The prefabricated liner may then be placed in the tank and brought up over the top edge of the wall. A second piece of larger split hose is then clipped over the liner and the bottom hose to anchor the liner around the top of the tank. The sheet metal roof can then be erected. Lauritzen quotes the following costs. 0.030 inch thick PVC liner US $0.20 per square foot, galvanised steel walls US $0.65 per square foot, roof US $0.59 per square foot, concrete base US $0.65 per square foot. Cost per unit volume of storage was US $0.063 per US gallon. (based on construction of a 36,000 gallon storage unit). If a PVC liner is used the base and inside of the tank must be smooth and the tank must be covered to prevent degradation of the liner. Lauritzen reports that the PVC liner should have a 15 year life when covered. If a compacted earth base is to be used or rigorous site conditions are expected a reinforced synthetic rubber liner may be used. This type of liner may be used in a tank without a cover. Lauritzen reports that a 14 gauge galvanised steel tank should have a life of 25 years or more but that any steel that will be below ground level should be coated with bitumen or a similar product to eliminate rusting.

In June 1973 a 10,000 gallon capacity tank of this type was built in Jamaica. The tank was built on a reinforced concrete base which contained outlet pipes. The diameter of the tank was 14 feet and the walls were 11 feet high. Quotations were received for a prefabricated PVC liner 0.020 inches thick from Stephens Plastics, Great Britain - US $ 96.33 (£38.50) FOB in May 1972, and Staff Industries Inc., United States - US $325.00 FOB in 1971. Stephens also included the cost of a reinforced butyl rubber liner which was US $ 202.66 (£81.00). It would appear from this evidence that the prices in Britain for PVC are considerably lower than those in the United States. The outlet pipes were joined to the PVC liner using bolted flanges and rubber gaskets to protect the PVC. The cost of materials and labour to build the reinforced concrete base, including the outlet pipes, erect the tank walls, install the liner and erect the roof of the tank was US $1,527.93 (J$ 1,379.00). The complete galvanised steel grain bin cost US $ 0.16 (J$0.14) per imperial gallon, which is approximately twice the figure quoted by Lauritzen. The tank is easily erected and this type of construction lends itself to schemes where a large number of standard tanks are to be built.

Prefabricated sectional pressed steel tanks are used universally for water storage. A well known British manufacturer of these tanks is Braithwaite and Company Ltd. The sections can be quickly erected on site and can be supplied with a variety of protective finishes. The tanks once assembled are strong and reliable and may be enlarged relatively easily. Any size of tank can be built up from the standard panels.

Sectional reinforced plastic tanks have certain advantages over the pressed steel section tanks. The panels are lighter and they do not require maintenance. However tanks with a depth in excess of 4 feet require external steelwork bracing. A British manufacturer, Hydroglas, will supply tanks and bracing where necessary to build tanks of 400 to 100,000 gallons capacity. The tanks can be supplied with light or heavy duty covers. A quotation for a 10,000 gallon tank with a weatherproof cover amounted to just over US$3,432.80 (£1,400.00) FOB London in March 1973.

Both types of prefabricated sectional tank come as a complete unit, the base being an integral part of the tank.

Prefabricated reinforced synthetic rubber storage bags are marketed in Great Britain and the United States. The cost of a 1,500 gallon bag in Great Britain from Butyl Products was quoted as US $ 307.75 (£123.00) in 1972. In the United States Uniroyal have a range of bags covering capacities from 250 gallons to 100,000 gallons. These bags may be used on any reasonably smooth surface which is capable of taking the loads imposed by the bag when full. The bags usually require a small pump to extract the water from them unless a gravity feed system can be devised. The larger tanks should be surrounded with bund walls to contain the water in the event of the rupture of the bag. An exposed storage bag of this type is liable to either accidental or malicious damage.

RESERVOIR COVERS AND METHODS OF EVAPORATION CONTROL

Summary:

The provision of a cover on a reservoir containing water which is to be used for domestic purposes usually cannot be justified on the savings made due to the reduction of the loss of water by evaporation. It may be cheaper to build additional catchment to make up the quantity of water lost by evaporation than to provide a cover. The Irrigation and Water Supply Commission, Brisbane, Australia, have commented that they know of no technique for evaporation control on small reservoirs of a given volume which is more economical than building a deeper reservoir with a smaller surface area. However there are several additional reasons for providing a cover. The Public Health Service in the United States recommends that all potable water storage reservoirs are covered to maintain a high quality of water and reduce the risks of pollution. Grover (1971) reports that in some areas regulations prohibit any open water surfaces because they provide breeding places for mosquitoes and other disease-carrying insects. A properly constructed cover on a reservoir will prevent the entrance of airborne dust and dirt, the entrance of leaves and tree seed spores, insects and other life forms. A cover will also prevent

the accumulation of algae in the reservoir which can cause taste and odour nuisances. In open reservoirs the natural dissipation rate of chlorine is very rapid and it is impossible to maintain a sufficient amount of residual chlorine for effective water treatment in a reservoir which does not have a cover. There are two qualifications on the use of continuous reservoir covers that should be borne in mind in the design stage. If the cover is flexible then rainwater will collect on it and be evaporated off unless drain holes are provided in the cover or the water is channelled into the reservoir by some other means. Secondly the covers restrict the oxygenation of the stored water. The design should provide adequate ventilation especially where the water is to be stored over long periods. Traditionally reinforced concrete or sheet aluminium roofs supported on suitable frames have been used as covers of small reservoirs. These roofs often require roof supports in the form of columns throughout the reservoir. Both types of roof are expensive. Globe Linings Inc. claim that a cover consisting of a sheet of reinforced synthetic rubber made buoyant by a number of semiflexible foam floats can cut the cost of a conventional roof by three quarters. The cost of US $1.00 per square foot is still expensive and several other floating covers have been devised. Polystyrene rafts coated with bitumen to prevent their degradation and either linked to one another or fitted individually with edge fins to prevent them lifting off the water have been used successfully. The use of lightweight concrete rafts has also been reported. Floating wax blocks have been used but they tend to pile up under the influence of the wind. Experiments have been carried out with a number of polyethylene sheet materials but they have not proved successful because rainwater collects on their surface and eventually they sink. They also have a limited life because of the degradation of the polyethylene. Butyl rubber covers have been supported or suspended from aluminium struts spanning reservoirs up to 40 feet wide.

On large reservoirs the use of a monomolecular layer of a long chain alcohol has reduced evaporation losses. The alcohol is dissipated by wave action and is transported across the reservoir by the wind. Wind driven dispensers may be used to replenish the alcohol layer. Experiments reported in Australia have shown that a floating sheet of foam polystyrene mesh used in conjunction with the alcohol prolongs the useful life of the alcohol.

In some areas of low rainfall, infrequent showers and high evaporation it may be worth using a rock filled tank, as described in the section on polyethylene, to reduce loss of stored water by evaporation. The loss of up to 50% of the storage space by using the rock must be weighed against the savings in evaporation losses. The sand filter tank devised by Ionides prevents evaporation loss and if the subgrade allows the use of steep side slopes the storage space created by the domed structures should be considerably more than 50% of the lined excavation.

General:

Globe Linings Inc. are one of the companies in the United States that specialise in the use of floating, reinforced synthetic rubber reservoir covers. The cover is fabricated from 1/16 inch thick nylon reinforced EPDM sheet. It is anchored to the top edge of the reservoir and sufficient sheet is used to allow the floating cover to rise and fall with the water level from an empty to a full reservoir. The sheet used is heavier than water and is made to float by placing a foamed plastic material in pockets fabricated in the liner. When the reservoir has water in it, it is possible to walk along these float sections. Globe paint the covers with an aluminium coating material to prolong the life of the synthetic rubber. The covers are guaranteed for 15 years and the company claim that if a new coat of paint is applied every 10 years then the cover could last indefinitely. The covers have been in use for 10 years and have performed satisfactorily in temperatures up to 115 degrees F. and winds in excess of 65 m.p.h. It is claimed that the covers eliminate the growth of algae and prevent evaporation. In May 1972 the company gave a cost including materials and installation of US $1.00 per square foot for this type of cover. Uniroyal, a manufacturer of synthetic rubber sheet in the United States, gave similar cost figures. They estimate that sheets which weigh less than water and therefore float cost US $0.80 - US $1.00 per square foot while sheet which requires polystyrene floats will cost US $1.00 - US $1.25 per square foot.

Globe do not appear to have adopted a design which incorporates one way valves in their floating covers and, as advertised, rainwater will collect on the covers although it is claimed that most of the water collects at the edges of the reservoir. The company points out that the cover is self-supporting and little or no load is transferred to the side walls even during seismic disturbances.

Globe also advertise the use of reinforced synthetic rubber roofs which are airtight and are supported by pumping air into them. Uniroyal estimate the cost of such a system at US $2.00 per square foot.

Although the cost of these covers is less than the cost of reinforced concrete or a frame supported sheet metal roof they are not cheap. In addition, they suffer the drawback of all thin flexible sheet materials in that they are subject to vandalism.

Cluff (1972b) of the University of Arizona has been developing a floating raft made from expanded polystyrene. The material degrades on exposure to daylight and the upper surface of the rafts was first protected by coating it with sprayable butyl rubber and more recently a coating of cationic bitumen emulsion dusted with coarse sand has been used. Cluff claims that these rafts reduce evaporation from the area covered by up to 95%. Vertically sided reservoirs may be covered completely while those with sloping sides may have an anchored raft of reduced area that is able to rise and fall with the water level without fouling itself on the sloping sides. Cluff first used individual rafts which were fitted with an extruded plastic edge piece which induced a suction force under the raft and effectively prevented the wind from lifting the raft from the surface of the water. The most recent development is to dispense with the edging piece and link all the rafts together using PVC pipes filled with water, split PVC pipes and nylon cord. A continuous raft is built up and the weight of the bitumen topping and of the water-filled pipes causes the raft to float low on the water. Rain falling on the raft can run through the joints to the reservoir and Cluff points out that the insulating properties of polystyrene prevent the heating of the water. This is important especially on partially covered reservoirs where some floating covers will allow the water to heat up thus increasing the rate of evaporation from the uncovered areas. Cluff quotes a cost of US $0.95 per square yard for this latest type of raft which is made up from units 4 feet square by 1 inch thick.

In Australia, Laing (1969) reports that polystyrene foam 2 inches thick costs US $ 2.02 (A$1.80) per square yard which is considered expensive for evaporation control. Woodings (1972) reports that small farm tanks of 17 feet diameter have been successfully covered with 2 inch thick sheets of polystyrene. The cost of making the sheet from two thicknesses of 1 inch sheet, of cutting the single continuous piece, and of coating with plastic paint was US $ 3.22 (A$2.70) per square yard.

Drew (1970) reporting on experiments carried out in Australia states that polystyrene foam sheets when used as a 100% cover produce a saving in evaporation of only 75%. A 50% cover produces a saving in evaporation of 50%.

Cluff (1) reports that rafts of lightweight concrete have been used on reservoirs in southern Africa. The concrete is made by mixing cement, sand and styrofoam and the completed raft is coated with pitch to reduce vapour flow through the concrete. The lightweight concrete rafts are more expensive than polystyrene rafts but are reported to be more durable.

Cooley of the United States Water Conservation Laboratory has reported that foamed wax blocks have been used to reduce evaporation. The blocks, which are 10 to 12 inches in diamter and $\frac{3}{4}$ to 1 inch thick, are made by forcing molten, high melting point (150 - 160 degrees F.) paraffin wax and air through a nozzle. Blocks covering 70 to 80% of a water surface have reduced evaporation by 50 to 60%. The blocks have remained on the water in winds of 50 to 60 m.p.h. but they tend to drift and pile up under the action of the wind.

If the cost of the floating rafts or blocks is known and their effective life can be estimated then by using the figures of expected reduction in evaporation it is possible to calculate the cost of the water saved. For example Drew (1970) assumed a 5 year life for a polystyrene sheet and that a 75% saving in evaporation would be made using a complete cover. He calculated that the cost of saving 1,000 gallons of water would be US $ 2.80 (A$2.50). The figure calculated in this way should be compared with the cost of providing 1,000 extra gallons of water by extending the catchment or storage to see whether the cost of preventing evaporation can be justified. Floating rafts which do not cover the whole of the water surface will not prevent the pollution of the water by dust, birds and animals and will not produce the improvements in the quality of the water which, as has been explained already, may be a further justification for the reservoir covers.

Drew (1970) and Laing (1969) have reported the results of experiments in Australia using sheet plastic materials, which are much cheaper than synthetic rubber, as a means of reducing evaporation in small reservoirs. The materials are all lighter than water and will float naturally. Both Drew and Laing have used polyethylene sheets of thicknesses between 0.002 inches and 0.006 inches. Laing reports that prefabricated continuous sheet 0.006 inches thick sinks after rain has collected on top of the cover.

The sheet must be weighted down around the edge of the reservoir to prevent the wind lifting it. Laing suggests that polyethylene may be used as an emergency drought measure and that it should be renewed after one year's use. In the event of heavy rain it is likely that the cover will sink and will have to be removed from the reservoir before replacing it in its correct position. The polyethylene must be black if it is to have any durability and as a result the water it is covering will heat up. This will result in higher rates of evaporation from uncovered areas. Laing found that PVC behaved in a similar fashion to polyethylene but is more expensive.

Drew used 0.002 and 0.004 inch thick polyethylene sheet in strips. The strips varied from 6 feet wide to 3 inches wide but all sizes of strip sank after rainfall. There was a very low percentage saving using this method although the cost of cover material is also very low.

Drew tested a woven polyethylene material which is laminated with a continuous film of polyethylene. Used as a total cover the sheet reduces evaporation losses considerably. Rain falling on the sheet tends to collect in pools even when drain holes are provided and this leads to either its rapid evaporation or the sinking of the cover.

Unless the rainwater falling on the cover can reach the reservoir the method may not result in any overall savings.

Drew tested a woven polyethylene sheet hoping that the rainwater would pass through the open weave of the material but this did not happen and the problems were similar to those encountered with the laminated material.

Cluff (1) has used polyethylene sheet supported on wooden or polystyrene frames to form rafts for evaporation control. Flooding of the polyethylene was a problem although this was overcome for winds of up to 20 m.p.h. by leaving a gap between the low profile polystyrene frame and the polyethylene sheet. The polyethylene would only last for one year.

Cluff has also reported the use of monolayers of long chain alcohols. This method of evaporation control is better suited to large water surface areas than small ones. The monolayer is disrupted by the wind and drifts to the downwind shore under the influence of the wind. Wind activated dispensers on the upwind shore will replenish the supply of alcohol but a large amount of material is required. Cluff quotes a cost of US $1.00 for the saving of 1,000 gallons of water on a reservoir of over 15 acres. However on reservoirs of less than one acre the cost is 3½ times as great.

Healy (1965) has reported on the chemical composition of the alcohol to be used. A balance has to be made between the faster spreading times of the shorter chain alcohols and the greater efficiency in controlling evaporation of the longer chain alcohols. Cetyl alcohol has a reasonably fast spreading and reforming time and provides a reasonable control on evaporation. Surface ripples reduce the efficiency of evaporation control of cetyl alcohol by up to 30%. The longer chain alcohols are more effective at damping the capillary waves but can only be added to the cetyl alcohol in amounts which will not adversely affect the spreading rate of the mixture.

Drew found that a sheet of foam polystyrene mesh with 1 inch square openings dampened down the wave action on a body of water. It also allows rainwater to pass through it. Used on its own the mesh results in a very low saving of water but when used in conjunction with cetyl alcohol the two materials complement one another. The alcohol is contained within the mesh and the wind effects are reduced leaving the alcohol evenly spread over the water. It is assumed that the alcohol will be replenished about 3 times a month although Drew reports that it appears that the alcohol is only completely removed by sublimation over a period of a month. All of Drew's work has been on small experimental tanks but he recommends this method for further research. For short periods, savings of up to 46% were recorded and this would result in a cost of saving 1,000 gallons of water of US $ 1.09 (A$0.97) if it could be maintained over several years.

CONCLUSION

Water Storage:

This publication has dealt with methods of lining earth reservoirs. Some soils have been described which are naturally waterproof when compacted and do not crack on drying out. These soils will not require lining but care must be taken in the design of the water inlet structures to prevent scouring the soil surface.

The use of bentonite, sodium polyphosphate or sodium chloride to improve the waterproof properties of soils which are nearly of the above class has been described. These methods are most suited to small storages which have little or no fluctuation in water level. A cover of 12 inches of sandy material is required wherever the lining may be left uncovered by water. This is to try and prevent the treated soil from drying out and losing its effectiveness. It is not felt that these methods are suitable for large, permanent water storages but they may be useful for small, short term storages.

If the subgrade is a smooth, coarse grained, open soil then a synthetic rubber lining is the only method described that may be used as an exposed liner.

The rubber should contain EPDM to improve its weathering properties. The liner is the most expensive of the prefabricated, flexible linings described and when used in this way it is liable to malicious damage. It is very easily placed. Generally unreinforced materials should be adequate but if subgrade conditions are extreme or there is some doubt over site handling then a reinforced material may be used. Good design of the subgrade can relieve the stresses in the material and result in a longer life.

If it is decided that the subgrade must be lined and that a cover material for the liner is acceptable then either bitumen or polyethylene are the cheapest solutions. The water inlets to the storage must be designed to prevent scouring of the cover material. The methods described by Zimmerman are most universally applicable for the use of bitumen. Bitumen may be used on more open and coarse subgrades than polyethylene. The polyethylene must be laid on a smooth surface, preferably sand, and the joints between sheets of the material must be weighted down immediately after they are made. Both linings must have a cover of at least 12 inches of sand or a similar material. Bitumen linings have been used to seal areas of fissured rock and in some cases it may be worth while to include woven polypropylene or fibre glass sheet as a reinforcement in the bitumen.

If the water storages are to have permanent roofs which will prevent light reaching the materials lining the storages then PVC should be considered for use. It is cheaper than synthetic rubber and is joined more effectively than polyethylene without the need for weighting down the joint once it is made.

The use of asphalt and prefabricated bitumen panels can only be justified in certain circumstances. Asphalt is best suited to very large installations and the use of bitumen panels is only necessary in special cases.

It is not felt that epoxy resins are suitable for making complete linings because of their cost and rigidity. They may be useful for sealing local areas especially porous or narrowly fissured rock.

Generally, flexible linings will be used only where it is felt that ground water will not interfere with the subgrade.

Catchment:

This publication has described methods of creating artificial catchment areas either to improve runoff from natural surfaces or to provide a surface from which high quality water may be collected.

Generally treatments of natural surfaces will increase runoff but will not prevent the water from being sediment laden. Sediment may be removed partly by silt traps before collection and will settle out in the storage. This may not be desirable. The roaded catchment described probably improves the efficiency of runoff of a natural catchment by as much as is possible using only compaction. All the chemical treatments described are very short term and will be eroded away.

If it is decided to build an artificial catchment to provide high quality water then the polyethylene and gravel catchment and the sheet metal catchments are the cheapest. Both must be laid on a smooth surface. There is a limitation on the length and the slope of the catchment when polyethylene is used to ensure that the velocity of the runoff water does not disturb the gravel. The sheet metal catchments present the difficulty of finding a suitable method of holding them down and preventing damage to them by the wind. Aluminium sheet should weather better than untreated steel sheet but it is more difficult to joint and tie down. The metal sheets although more expensive are 100% efficient whereas the gravel and polyethylene is only 75% efficient.

Thin aluminium foil is difficult to bond to the soil and is easily damaged and appears to be better suited to small scale applications.

Bitumen can be used to create 100% efficient catchments but weathering of the bitumen surface causes the runoff to be discoloured. This may not matter in certain applications. The weathering is less on bitumens derived from Venezuelan crude oils than some others and can be further reduced by treating the bitumen surface with sand, gravel or various types of paint. The bitumen should be used only on soils with which it will form a bond. There does not appear to be much gained by reinforcing bitumen used as a catchment that would justify the added expense.

None of the catchments described to provide high quality water will withstand the passage of vehicles or the repeated passage of cattle. They are liable to malicious damage but this is relatively easily repaired and is a minor problem when compared to the similar difficulty associated with water storages.

If it is decided that a thin concrete catchment, which cannot be damaged, must be used then the method of placing Gunite provides a quick and easy way of building the catchment, for no increase in cost. Some saving may be made in that little formwork is required and the job will be completed quickly.

Water Storage Tanks:

Ionides has described an efficient and cheap tank for storing good quality water. It depends on the local availability of sand, mud and labour.

The steel grain silo lined either with PVC or reinforced synthetic rubber presents a cheaper alternative for water storage to the prefabricated tanks and concrete tanks in common use. It is easily erected and has the advantage of a good roof. It is ideally suited to programmes involving the erection of many identical tanks.

The rock-filled tank described is thought to be only useful in cases where evaporation losses over long periods are extreme. Although their successful use has been reported, the author has reservations about the plaster tanks. It is felt that after a short time they would require maintenance and repair.

Reservoir covers and evaporation control:

It is felt that floating synthetic rubber covers will only be used in cases where it has been decided that there must be a roof. At US $1.00 per square foot such a cover becomes the major item of expense.

The rafts devised by Cluff seem to provide a means of reducing evaporation loss and of providing a complete cover on vertical sided storages or partial cover on sloping sided storages at reasonable expense.

The use of long chain alcohols on small storages is not recommended. However the method described by Drew of using alcohol in conjunction with a floating mesh of foam polystyrene may result in significant reduction of evaporation at acceptable costs.

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* undated

APPENDIX

THE COSTS OF SOME MATERIALS AVAILABLE IN THE U.K. IN MARCH 1975

During the last two years the prices of most materials used by the construction industry have increased dramatically throughout the world. The prices of synthetic rubber, polyethylene, and polyvinyl-chloride have increased to between 2 and 2½ times more than the price quoted for them in the text. However, materials such as cement and steel reinforcement which may be considered as alternatives to the sheet materials have now reached a level in the U.K. of around 1½ times their cost in 1973. This Appendix gives the reader a list of prices of some of the sheet materials and prefabricated water tanks available in the U.K. in March 1975. As long as the current economic situation prevails it must be expected that these prices will continue to rise.

It is assumed that the reader interested in using any of the methods described in the text will undertake an exercise to determine the total cost of any proposed scheme. This exercise will involve comparing the costs of as many schemes as are thought practicable so that a decision may be made to proceed with the one that is most suitable.

In general the materials used will be supplied locally and it is not possible to provide here a survey of prices throughout the world. However, thin sheet materials such as synthetic rubber, polyethylene, and polyvinyl-chloride (PVC) can be transported relatively easily and cheaply so that it may be a practical and economic possibility to import them from a foreign country. This may also apply to sectional tanks that can be transported in their broken down state ready for erection on site.

The following list of prices of materials available in the U.K. in March 1975 will enable the reader to compare the prices of the same materials if they are available locally or to estimate the cost of importing them from the U.K. Consideration should be given to the cost of importing these materials from alternative suppliers who may be more favourably situated, such as those in the United States.

The prices in the following list, except where otherwise stated, include the cost of transport in the U.K. and the cost of loading onto ships at docks specified by the manufacturer.

SHEET MATERIALS

The price per square yard of the sheet materials decrease as the total area ordered increases. Some manufacturers may not be prepared to sell only small areas of material or they may require substantially increased prices for dealing with small orders.

To obtain the price per square metre multiply the prices for a square yard by 1.20. The prices quoted here have assumed an exchange rate of £1.00 to US $ 2.43.

Synthetic Rubber.

1. Butyl/EPDM prefabricated sheet

0.030" thick	US$4.01 per square yard
0.040" thick	US$4.86 per square yard

2. Butyl/EPDM Reinforced prefabricated sheet.

0.030" thick	US$6.70 per square yard
0.040" thick	US$8.06 per square yard

Black Polyethylene.

1. For a single roll measuring 30metres by 7.5metres (270 square yards)

0.010" thick	US$0.44 per square yard Ex works

2. For a minimum order of 15 rolls (4000 square yards approximately)

0.010" thick	US$0.24 per square yard

Polyvinyl chloride(PVC)

Prefabricated sheet.

1. 0.014" thick	US$1.23 per square yard Ex works
2. 0.020" thick	US$2.57 per square yard Ex works
3. 0.030" thick	US$3.68 per square yard Ex works

PREFABRICATED LINERS

To fit inside a 10,000 gallon tank (eg. 14 feet diameter, 11 feet high)

1. Butyl/EPDM	US$765
2. Reinforced Butyl/EPDM	US$912
3. PVC 0.020"thick	US$210 Ex works
0.030"thick	US$274 Ex works

SECTIONAL TANKS READY FOR ERECTION ON SITE.

All these tanks can be supplied with or without roofs.

1. Mild steel galvanised tanks with butyl rubber liners. (Titan Tanks)

These tanks come complete but must be erected on firm level ground free from sharp objects or preferably on a smooth concrete foundation to provide base support to the tank liner.

8,000 gallons capacity, 18feet diameter, 5 feet high walls.

Tank walls and liner	US$1754
Roof	US$1073
Total	US$2827

12,000 gallons capacity, 18 feet diameter, 7½ feet high walls.

Tank walls and liner	US$2102
Roof	US$1073
Total	US$3175

2. Pressed steel panels with bolted watertight joints. (Braithwaite)

The tank comes complete and has a base of steel panels. The manufacturer recommends that the base should be supported on dwarf walls of brick or concrete spanning in one direction only beneath the lines of panel joints in that direction. The tank is suitable for support on tower frames.

10,000 gallons capacity. 12 feet by 12 feet by 12 feet.

	Galvanised steel	Pressed steel with one coat of non toxic bituminous paint.
Walls and base with internal access ladder	US$5420	US$4737
Cover with man-hole and ventilator.	US$ 813	US$ 729
Total	US$6233	US$5466

3. Glass reinforced plastic panels with bolted watertight joints(Hydroglas)

The tank comes complete and has a base of plastic panels. The base may be laid directly on level ground, concrete, or dwarf walls. The tank may be used on tower frames where suitable support to the base is provided.

10,000 gallons capacity. 24 feet by 16 feet by 4 feet deep.

Walls and base	US$4200
Roof	US$1880
Total	US$6080

10,000 gallons capacity. 16 feet by 12 feet by 8 feet deep.

Walls and base	US$5040
Roof	US$1320
Total	US$6360*

*Glass reinforced plastic tanks over 4 feet high require steel bracing, the cost of which must be added to the US$6360 to obtain the total cost of the tank. The manufacturer will provide the necessary steelwork.

In this Appendix :-

" represents inches.

To convert feet to metres multiply by 0.3

The prices in this Appendix were provided by the following firms:-

Synthetic rubber: Butyl Products,Limited,Radford Crescent,Billericay,
Essex. CM12 ODW.

Polyethylene: I.C.I.Ltd.,Plastics Division,P.O.Box No 6,Bessemer Road,
Welwyn Garden City,Hertfordshire. AL7 1HD. (Large orders)
Stephens(Plastics)Limited,Hawthorn works,Corsham,Wiltshire,
SN13 9RD. (Small orders)

PVC:Stephens(Plastics)Limited,Hawthorn Works,Corsham,Wiltshire,SN13 9RD.

Titan Tanks Construction Limited,60,Queens Street,Horsham,Sussex,RH13 5AD.

Braithwaite & Co. Structural Limited,59,Church Road,Great Bookham,
Leatherhead, Surrey KT23 3JJ.

Hydroglas Tanks,BTR Reinforced Plastics Limited, Barnsfield Place,
Rockingham Road,Uxbridge, Middlesex UB8 2UL.