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Underground storage of rainwater for domestic use including construction details of a low-cost cistern and pumps

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ABSTRACT

This Working Paper describes the construction and initial testing of low-cost underground rainwater storage tanks and of cheap but crude pumps by which water can be extracted from them. Several of these tanks have been constructed around Kagadi in Western Uganda between January 1996 and March 1997 as part of a programme attempting to develop an 'all-year' domestic rainwater harvesting system costing under $150 per household. Initial leakage of the cisterns after several cycles of filling and emptying has been satisfactorily low.

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* Although the writing of this Working Paper and the opinions in it are the responsibility of the named authors, much of the construction work and some of the design work reported in it were carried out by members of Uganda Rural Development and Training Programme (URDT), a Ugandan NGO. The contributions of the following people were particularly important : Chilampa Hardman, Turyamureba Victor, Mugisa Kimarakwija and Byaruhanga Moses, as was the support of Mwalimu Musheshe and Rutaboba Ephrem of URDT□s management.

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1 INTRODUCTION

Rainwater has been captured for use as a domestic water source for thousands of years. Urban civilisations have been based, in arid zones, on the seasonal storage of rainwater in underground cisterns. In very wet areas, the capture of rainwater from roofs on a daily basis is common, especially where for some reason water is not conveniently available from streams or wells. In recent years, most of the interest in rainwater harvesting has been concentrated in dry regions where alternative water sources are particularly rare. By contrast, this paper is about rainwater collection in a country, Uganda, with a generally high rainfall and (due to its straddling the Equator) a favourable □bimodal□ rainfall distribution.

Rainwater collection requires a collection surface (usually a roof), a water guidance system such as guttering and a storage tank big enough to supply water throughout any gap between significant rainfall events. If that gap is only 24 hours, the storage volume can be quite small. Many households collect run-off in bowls and buckets placed under the edges of roofs; short iron-sheet gutters without downpipes sometimes aid this process. Traditionally rainwater is also collected from trees in Uganda, using banana leaves or stems as temporary gutters; up to 200 litres may be collected from a large tree in a single storm. If the gap between rain events is a □dry season□ of several months, the storage volume has to be several thousand litres. In many parts of Uganda the rainfall pattern is such that for a household using 90 litres per day to rely wholly on rainwater for its domestic needs, a water storage capacity of about 8,000 litres (as will be discussed later) is needed. The cost of such a big tank is a problem for most households as has been pointed out in two recent Ugandan studies (Ntale [1996], Rugumayo [1995]).

Yet Uganda is a better place for domestic rainwater harvesting than most others in Africa because in most Districts:

- the (two) dry seasons are usually quite short and rarely completely dry;
- rainfall exceeds 1200 mm a year so that even a fairly small house has a big enough roof to collect the water (assumed to be 15 litres per person per day) that a poor family needs;
- corrugated iron roofs are becoming common, even in rural areas;
- the lateritic soil is permeable, so that wells to reach the water table have to be very deep unless they are in valleys: deep *dug* wells are very rare although the excavation of latrine pits 10m deep is common; boreholes are expensive and often unreliable;
- in the many hilly areas, where there is usually water in valleys, much effort is expended in carrying it up steep and sometimes very slippery slopes to where most farms are located (on the ridges and hillsides): by contrast rainwater collection offers on-the-spot water at the homestead;
- the soil type and the low water table make it quite easy to dig underground water storage tanks which are generally cheaper than above-ground tanks of the same capacity;
- gravity-fed piped water is rare outside the main towns both because it is technically difficult (absence of strong high level springs, lack of mains electricity) and because the organisation to install and operate gravity water supplies is lacking in rural areas.

From late 1995 to early 1997, the DTU authors named above worked with members of Uganda Rural Development and Training Programme (URDT, a service NGO located at Kagadi in Mid-Western Uganda) to develop a cheap water-storage technology for the surrounding region. This Working Paper describes the initial findings of a programme of rainwater harvesting development that is still continuing.

2 CHOOSING THE SIZE OF A RAINWATER CISTERN

The literature contains discussion of several ways of sizing rainwater stores. The different methods almost all assume that water consumption is at a constant daily rate throughout the year. They require as data inputs: that daily rate, details of roof plan area, rainwater catchment efficiency and rainfall distribution. Their outputs are recommended store sizes for one or more probabilities of storage failure (i.e. tank runs dry). The methods are well reviewed by Ntale (Ntale [1996]) who shows that in a not untypical particular location in Uganda, 100 km east of Kampala, the crudest method (*Mean Dry-season Deficit*) gives a storage size very much less than given by more elaborate and accurate methods.

Table 1 Ntale□s Comparison of Tank Sizing Methods (in Mokono District, Uganda)

Constant Yearly Assumed Demand = 67% of Average Annual Rainwater available from roof.
□+□ indicates extension of the data by the present authors.

Mean Dry-season Deficit method using MEAN monthly precipitation
Recommended storage = 0.015 x yearly demand.   Failure fraction (of time) = approx. 40%
(any month during which the storage tank is at some point empty is deemed a failure month)

[+] *Adjusted Dry Season Deficit* method using (MEAN - 0.5 x SD) of monthly precipitation
Recommended storage = 0.063 x yearly demand.   Failure fraction = approx. 10%

[+] *Adjusted Dry Season Deficit* method using (MEAN - 1.0 x SD) of monthly precipitation
Recommended storage = 0.173 x yearly demand.   Failure fraction < 1%

Cumulative Deficit method (maximum local drop in the cumulative supply-minus-demand curve over the period for which rainfall records are available)
Recommended storage = 0.167 x yearly demand   Failure fraction < 1%

Actual Storage Behaviour method (historical rainfalls combined with various tank sizes)

Tank size/annual demand	.027	.056	.111	.167	.278
Failure fraction	21%	11%	3.6%	<1%*	<1%*

* the precise failure fraction depends at what month in year 1 the tank was commissioned

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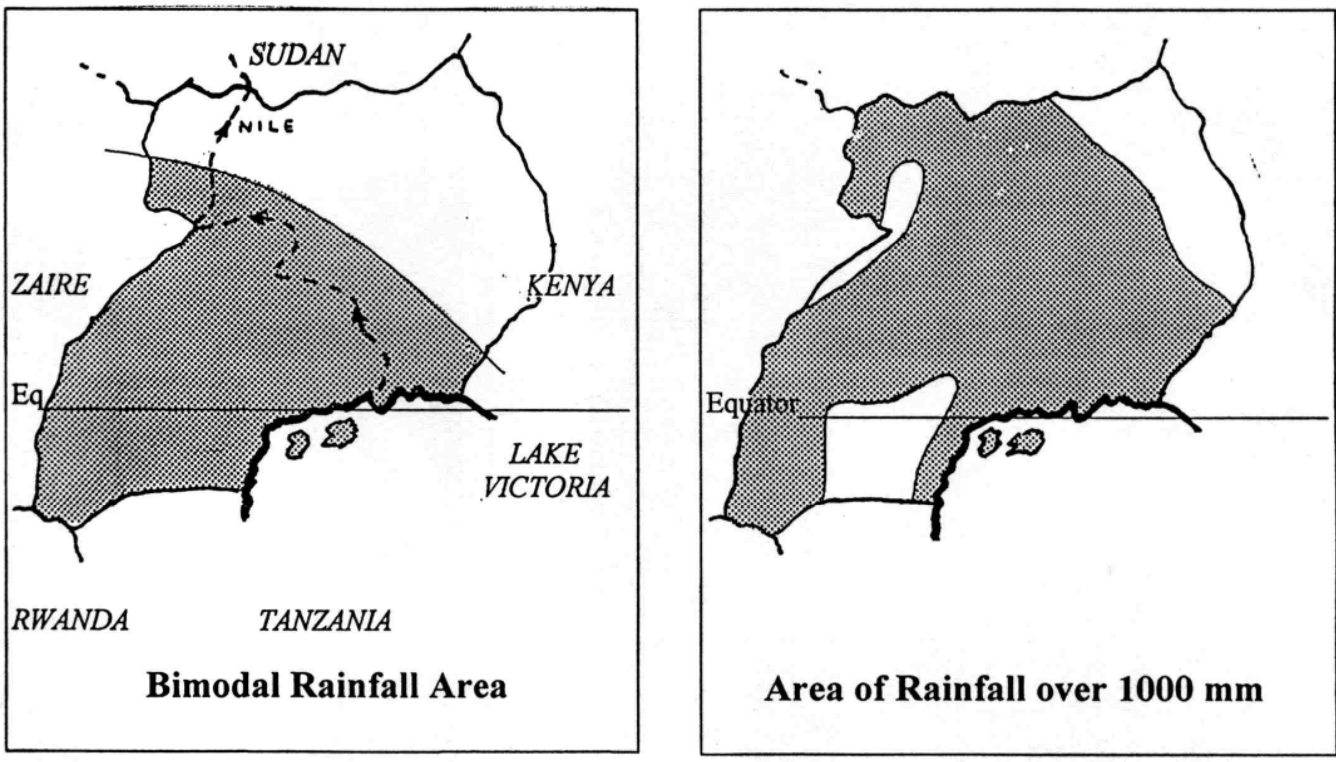
Clearly the *Mean Dry-season Deficit* method is unsatisfactory in situations where rainfall is very variable from year to year. In Ntale□s rainfall data there is a very high coefficient of variation (= S.D./mean). This coefficient exceeded 60% for each of the 5 driest months of the year, although for the year as a whole was much lower. Popular belief in Uganda is that rainfall is getting even more erratic. The □failure fractions□ shown in the table would also rise sharply if the ratio of annual usage to capturable runoff were raised from the fairly low figure used (67%) in the modelling. Assuming that 80% of rainfall is □capturable□ and that households make some adjustment to their water usage in exceptionally dry seasons, we have developed the following recommendation:

For a bimodal rainfall pattern and where the annual rainfall (mm) x the roof plan area (m^2) is at least 1.5 times the intended annual water consumption (in litres), we recommend 25% of annual demand as a suitable tank size - say 8000 litres for a rural household using 90 litres a day..

In the debate between rough and ready methods of sizing storage (Pacey [1986]) and more □exact□ methods (Heggen [1993]) it should be remembered that:

- Uninterrupted rainfall records are not available (or are not readily accessible) in most developing countries, especially to householders or builders deciding tank sizes who need simple rules such as "700 litres storage is needed per roofing sheet".
- In the case of poor wet seasons leading to incomplete tank filling, householders are likely to reduce usage in the subsequent dry season; Ntale documents significant seasonal differences in consumption rates at present due to variations in the effort required to obtain water in different months. It would probably be realistic to set dry season water consumption at 90% of wet season consumption, e.g. 14 and 16 litres per day respectively where the annual average is 15.
- It is not clear that households will discipline themselves to keep to the water usage rates assumed in any storage sizing exercise; certainly household occupancy can fluctuate and unplanned activities consume unplanned quantities of water. A per-capita rate of 15 litres water consumption per day has been assumed (giving 90 litres per day for a 6-person household). This is higher than current practice but reflects movement towards the national target of 20 litres/day and the likely rise in consumption when it is not □effort-limited□.



Map of Uganda showing bimodal rainfall areas

3 COMPARISON OF TYPES OF WATER STORAGE CONTAINER

The main domestic options for storing rainwater are plastic bowls/jerrycans, clay jars, cement jars, above-ground tanks and underground cisterns. For “wet season” domestic rainwater harvesting (the low-cost variant of DRWH which requires only about 200 litres storage per household) the first three options above are relevant. For “all-year” supply requiring over 5000 litres storage, only the last three options are suitable. Cement jars overlap both scenarios as they may be made in sizes from 100 to 1500 litres.

This Working Paper is about constructing low-cost underground water tanks ("cisterns") next to individual houses. Underground tanks, compared with above-ground ones, have advantages and disadvantages.

On the plus side

- they are generally cheaper as mentioned above;
- they cannot be emptied by such accidents as a child leaving a tap open all night;
- they take up little room;
- they do not require the transport of heavy items like cement jars.

On the minus side

- any cracks and leaks are hard to find and repair;
- a pump is needed to lift the water out of the tank;
- there could be a danger of pollution by surface water getting into the tank;
- there could be pollution if effluent from a latrine was able to migrate into the tank;
- any leakage out of a cistern may create moist zones that attract tree roots which could later further open cracks in the cistern walls;
- if the water table were to rise very high during floods *and* the tank was empty, the tank could float up out of the ground;
- if access holes were left open, a child might fall into the tank and drown;
- a heavy vehicle might drive over the tank and break its cover.

Fortunately the ground water level, in Western Uganda at least, is usually well below the bottom of any underground cistern as can be seen by the great depth (over 10 meters) to which latrines are commonly dug in the area. Thus the dangers either of pollution by groundwater or of floating up do not seem significant.

Ntale[1996] suggests that to achieve 8000 litres of water storage in 1996 costs about:

- $340 in total for unreinforced mortar jars (at least 4 jars),
- $390 for a brickwork tank, 50% more if reinforcing is deemed necessary,
- $450 for a galvanised iron tank,
- $1432 for a PVC tank,
- $480 to $880 (various sources for E Africa) for a ferrocement tank,
- $182 (quoted from Brazil) for a plastered tank of stabilised rammed earth, a material currently hardly known in Uganda..

These sums seem generally beyond the purchasing capacity of Ugandan rural households where even finding $200 for an iron roof is often not possible, although the last technique has promise.

4 PUMP SPECIFICATION

If an underground tank is to be used, the hand-pump required to extract water from it must be specified. In rural houses where there is a solar electricity supply and some wealth, low-voltage submersible electric pumps constitute a serious option. They can be used to raise water from the underground cistern into a small □day tank□ located in the roof rafters from which a gravity feed is possible. Solar electricity is spreading, but in Africa reliance on hand-pumping should still be the basis of any specification.

A pump for a household cistern should

a/ be cheap (in Uganda we chose a ceiling price of USh.15,000 = $\$_{US}15$);
b/ permit an adult to raise 10 litres per minute (a rate generally obtained from protected wells) from a depth of 4 meters without undue effort and also be usable by a child of 6 years;
c/ be □self-priming□, delivering water within a few strokes of starting to pump even when the pump has been out of use for some days;
d/ reach water within 20 cm of the bottom of a tank;
e/ fit into the mortar plug in the cover (dome) of a cistern so that light, mosquitoes and surface water cannot enter, yet permit the riser pipe and foot valve to be withdrawn through that plug whenever they need any maintenance;
f/ lift at least 100,000 litres under household conditions of use before requiring replacement;
g/ lift at least 10,000 litres before requiring maintenance, all such maintenance being possible using skills and materials available in most African villages;
h/ be economically manufacturable in each country of use;
i/ discharge conveniently into a jerrycan or other collection vessel.

In addition it is desirable that
j/ the foot valve does not leak faster than 0.1 litre per minute, so that if the pump is used twice within say 10 minutes it does not have to be (self) re-primed for the second use;
k/ the intake is constrained to avoid drawing up sediment in the tank by being located say 10 cm above the tank bottom; however for cleaning purposes it is helpful if dirtied wash water can be lifted from as little as 2 cm from the tank bottom.

5 MATERIALS, TOOLS AND SKILLS

This paper describes how to make a particular 6,000 to 10,000 litre underground cistern, suitable for construction where the soil is firm and hard but not rocky, and a cheap hand-pump to fit into it. *Variant A* has a 20 mm thick cement-mortar dome (mix = 1:3), a 25 mm cement mortar lining to its Chamber, and employs a little chicken mesh reinforcing. *Variant B* has a 20 mm cement/lime-plastered Chamber. Both variants have similar shapes and construction procedures. The materials necessary for the tank□s construction meet the test of ready availability even in African small towns. They are, for an 8,000 litre cistern:

Material Quantities	*Variant A*	*Variant B*
bags (ea. 50 kg) cement	$5^1/_2$ (275 kg)	$3^1/_2$ (175 kg)

bags (ea. 25 kg) lime	0	3 (75kg)
wheelbarrows of sand	15	15
lengths (ea. 12m) of 6mm reinforcing bar	1	1
chicken mesh (1.8m width)	1.5m	0
plastic bucket, say 10 litre	1	1

(also wood to make the template mentioned under *Step 1* below - 130 cm x 100 cm thin ply or 3m x 300 mm x 20 mm plank - and a large plastic washing bowl)

The materials needed for the pump are slightly more specialised and may need to be obtained from a capital city. They are;

Material	*Quantities*
50 mm OD PVC pipe	0.5m
40 mm OD PVC pipe	4m
30 mm OD plastic pipe (nominal 1" bore; varies with foot valve type)	0.3m
20 mm plastic conduit tubing	3m
40 mm PVC tee and a piston (e.g. stirrup pump leather cup)	1 off each

(plus binding wire, solvent cement for PVC, rubber strips (ex inner tubes), wooden handle)

The tank and its pump must be locally maintained, and at least the former must be locally made. For these reasons a design specification was chosen that included the condition that both tank and pump should be fabricable using skills, materials and *hand*-tools readily obtainable in a small African town and maintainable using village-level facilities. A suitable pump is not available in Uganda, but as its performance specification is so modest it could no doubt be readily mass-produced if a sufficiently large market existed. In the short term however a locally-made pump (whose production entails no special jigs) is required if underground cisterns are to be promoted. The tools needed for tank and pump production are:

Tank	*Pump*
digging and plastering tools	hacksaw blade and file
a large plastic basin (say 45 cm diameter)	knife
a bucket on a rope for lifting out soil	& depending on type of foot valve:
a spirit level	tin snips, hand drill or large nail
a template for the dome (see *Step 1*)	

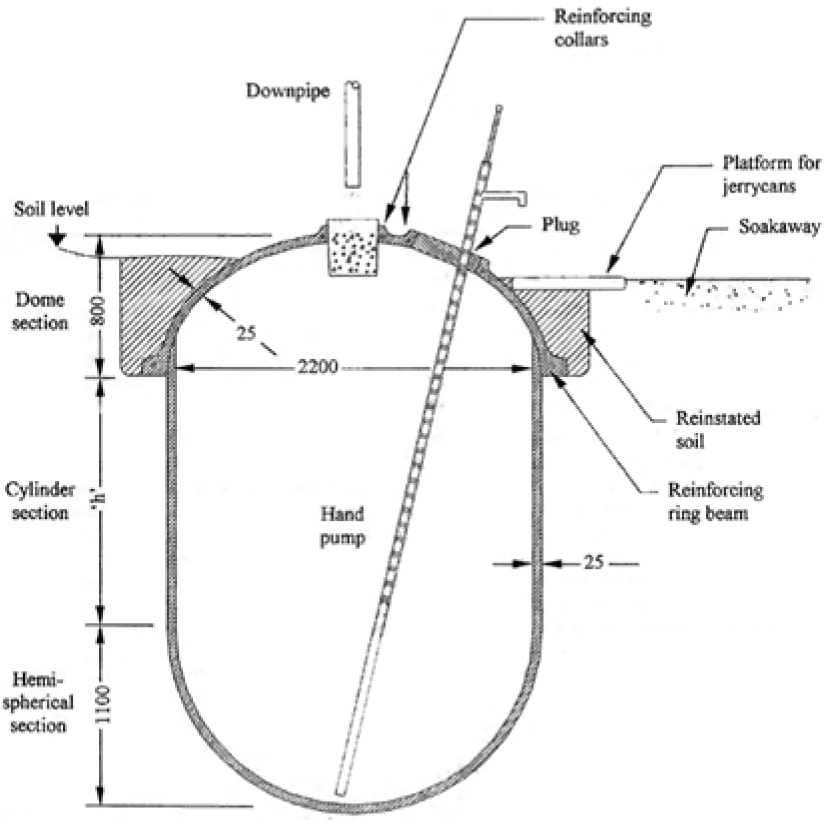


Figure 1 General side view of cistern with pump

6 PARTS OF THE DTU/URDT RAINWATER STORAGE CISTERN AND STEPS IN ITS CONSTRUCTION

We can divide an underground cistern into four parts, namely the Chamber, the Cover, the Pump and Extras. Figure 1 shows a sectioned-elevation view of the tank and pump (what you would see if you could dig it out and cut it in half from top to bottom).

The Chamber has to have adequate volume and be waterproof. Because the overall cost of a cistern is dominated by the cost of the walls and cover, we should like these to be as small as possible. For a given cistern volume, their total area is a minimum, for either a rectangular or cylindrical tank, when the tank□s depth equals its width. However for certain sorts of cover it is difficult to span widths of more than say 7 feet (2.2 meters). The cistern we are about to describe has a rounded Cover and a rounded bottom and has an internal diameter of 2.2 meters. The depth of the straight part of its sides for different capacities is as follows:

usable capacity in litres 4,000 6,000 8,000 10,000

depth of cylindrical sides 0 meters 0.5 m 1.0 m 1.5 m

depth from dome to bottom 1.9 m 2.4 m 2.9 m 3.4 m

For volumes of more than 10,000 litres, build more than one tank, (however tanks larger than 10,000 litres are discussed briefly in Section 14). For volumes of less than

5,000 litres one might choose to make a narrower tank This means changing the dome template to a smaller one. All the dimensions for such a small-tank template could be 20% less than those shown in Figure 3. The capacity table above would have to be replaced by another.

The Cover has to stop the water from evaporating, keep the water clean, prevent anyone falling into it and keep out light and mosquitoes. It has to be pierced by a big hole to let the rainwater in very rapidly and smaller hole through which water can be pumped out. These holes must also be mosquito and light proof, and at least one of them must be large enough for a man to squeeze through in order to inspect or replaster the inside of the tank. As you will see later, we recommend that the Chamber is excavated through the main hole in the Cover. The Cover should be shaped so that it leads any run-off from nearby ground away from its inlet. It must be strong enough to bear the weight of many people, provided that it has been covered with earth so that only the top of the dome is above the ground.

The Pump has to be simple and cheap. With a 10,000 litre tank and a spout 0.6 meters off the ground, the pump has to lift the water through a maximum of 4 meters when the tank is almost empty. When the tank is completely full the lift is only about 0.5 meters. 4 meters is much less than the lift from a borehole or from many wells, so the pump can be worked faster than in those situations and does not need to be so strong. A full pump specification was given in section 4 above.

The Extras include some means of seeing the water level inside the tank without having to open the Cover, a coarse filter for water entering the tank and provision for safe disposal of any overflow water. There is some interest in putting a layer of sand at the bottom of the tank as an output filter, however this would require the pump intake to be connected to a perforated pipe running under the sand. (Experiments to test such a filter's performance have yet to be done.)

During construction of any cistern, there are three choices in how one might combine the Cover and the Chamber. In some cistern designs, the Chamber is dug first and then the Cover built over the Chamber. In other designs the Cover and Chamber are made side-by-side and then the cover is lifted onto the top of the Chamber. For our design, we recommend a third method: the Cover is made first (in its final position at ground level) and then the Chamber is dug through an access hole in the Cover. It is not too difficult to do this if excavation is manual (although the procedure effectively excludes mechanical excavation and is therefore not recommended for high-wage countries) and it allows us to use a cheaper dome-shaped Cover than if we had to lift it. So the sequence is as follows:

Steps in Constructing the Cistern

- *(If necessary), make a new template to shape the dome with, as shown in Figure 3*

- *Mark and dig out the ring trench; use the template to shape the mound of soil above it*
- *Prepare reinforcing bar (and perhaps mesh) to place in the trench and round each hole in the dome*
- *Place mortar to form the ring beam and the dome with its two holes*
- *Cure the mortar then cover the dome with soil*
- *Through the larger hole dig out the Chamber*
- *Plaster the inside of the chamber and allow this plaster to cure*
- *Make the pump (two variants are considered)*
- *Set the pump into the dome*
- *Construct the tank inlet with its gravel filter*
- *Provide drainage and arrange the hard-standing for pumper and water containers*

The tank takes about 24 □man-days□ to construct. However the mortar dome and later the plaster in the chamber should each be left to cure for 2 weeks, so it needs a minimum of 6 weeks from when construction starts to when the tank can be used. Most of the work is digging but for 2 days an experienced plasterer is required. The pump can be made in a few hours.

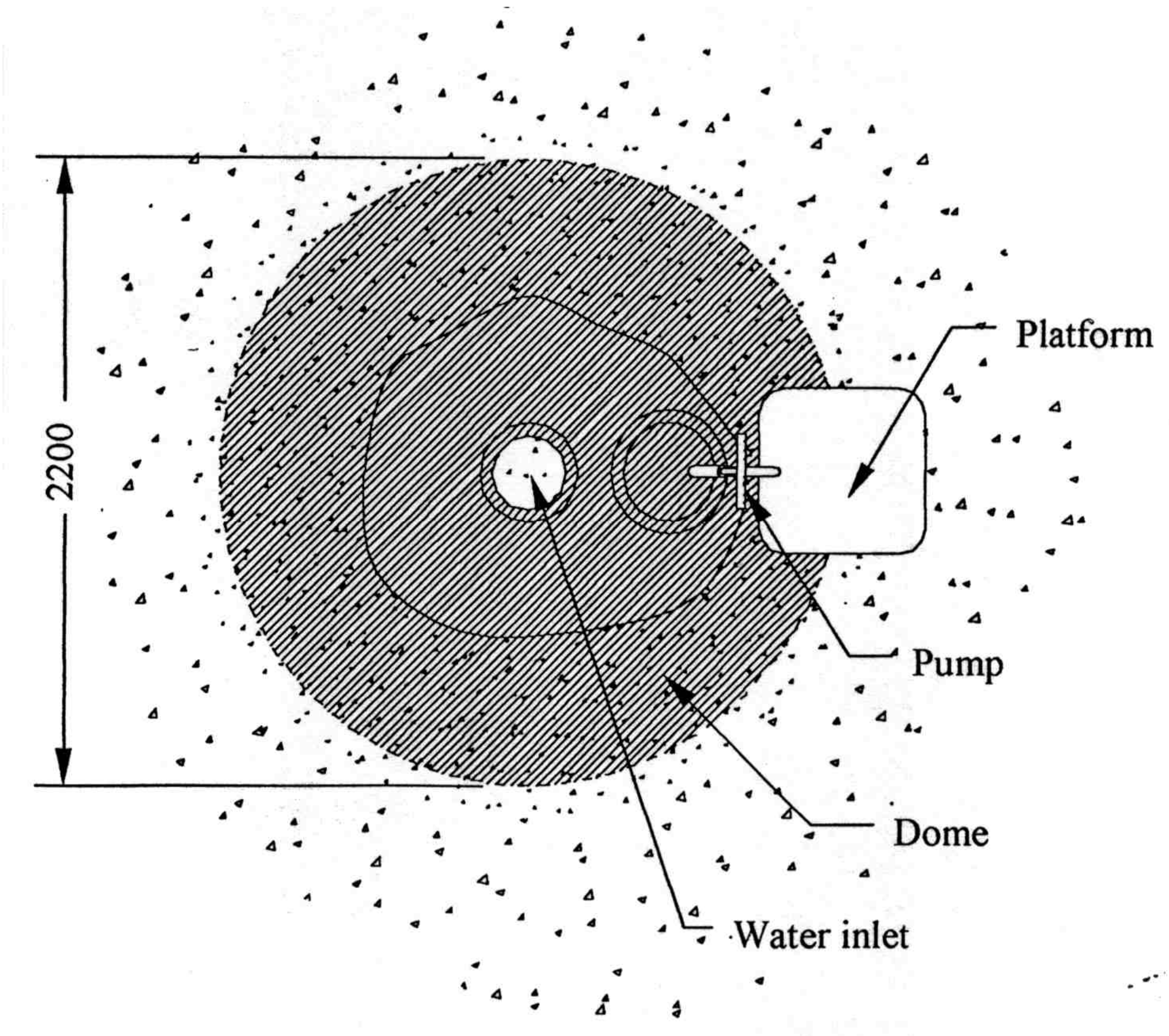


Figure 2 Plan of tank

7 Making the COVER (steps 1 - 5)

The Cover is a dome of mortar (containing almost no reinforcement) connected to a reinforced ‘ring beam’ set into the ground. The mortar dome and the ring are made at the same time over a carefully shaped mound of earth. Set into the mound are a bucket and a large plastic bowl. The bucket is to create a way for the rainwater to enter. The bowl is to create a hole to hold the plug in which the pump is set. It has to be large enough (e.g. 0.45 meter diameter) for a man to enter through. Figure 2 shows the Cover in ‘plan’ (when looked at from above). The 5 steps in making the dome will now be explained in turn.

Step 1 Making the ‘template’ for shaping the dome

The shape of the mortar dome comes from the shape of the mound of earth it is built on. We therefore need a template to accurately form that mound of earth. Before building the first tank it is necessary to cut this wooden template. Once made, the template becomes a tool that can be used for many more tanks. The template must be the right shape and also strong enough to carry around and use without getting broken. It therefore consists of a piece of plywood, or thin planks, cut to that shape and stiffened by strips of thicker wood.

The right shape for the dome is approximately a upwards ‘catenary’. A downwards catenary is the shape taken by a chain hanging between two nails on a wall, so we mark the template out using such a chain (e.g. 1 or 2 lengths of bicycle chain) and then turn it upside down.

First cut the plywood so that it measures 125 cm by 100 cm and has square corners. Figure 3a shows 2 nails spaced 2.2 meters apart on a horizontal line drawn across a flat wall using a spirit level. Draw a vertical line down the wall from midway between these two nails and mark a short line (the ‘mark’) across it 80 cm below the horizontal line. Hang a light chain between the two outside nails and adjust its length until it just reaches down to this mark. (If you do not have enough chain to do this, see the alternative below.) Slide the thin plywood behind the chain without touching it, so that the long top of the plywood touches the left-hand nail and the right side of the plywood lies along the vertical line. With a pen, copy the shape of the hanging chain onto the plywood, remove the plywood from the wall and saw along the line you have just marked. (Using planks instead of plywood, first nail them rigidly to their stiffening bar so that they can be placed behind the hanging chain; then continue as for plywood).

Although it is easiest to make the catenary with two bicycle chains joined end to end, it can also be done with only one. This has to be hung so that it forms just over half the full U-shaped catenary: one end of the chain is attached to the left-hand nail, the other end is held low and pulled until the *lowest* point of the chain falls exactly over the ‘mark’. You can now drive in another nail (‘alternative nail position’ in Figure 3) to attach the chain to, while you are copying the chain’s shape onto the plywood.

It is necessary that the chain has no twists and that it hangs freely, otherwise it might take up the wrong shape. The right shape ensures that the mortar dome is strong (by being everywhere □in compression□). Rope is not usually suitable instead of chain, because most ropes twist and are not heavy enough to hang properly.

To finish the template, stiffen it with good wooden strips. Now turn the template over so that the long straight side is on top and write the word □TOP□ next to it. Smooth the sharp corners to make it safer to carry.

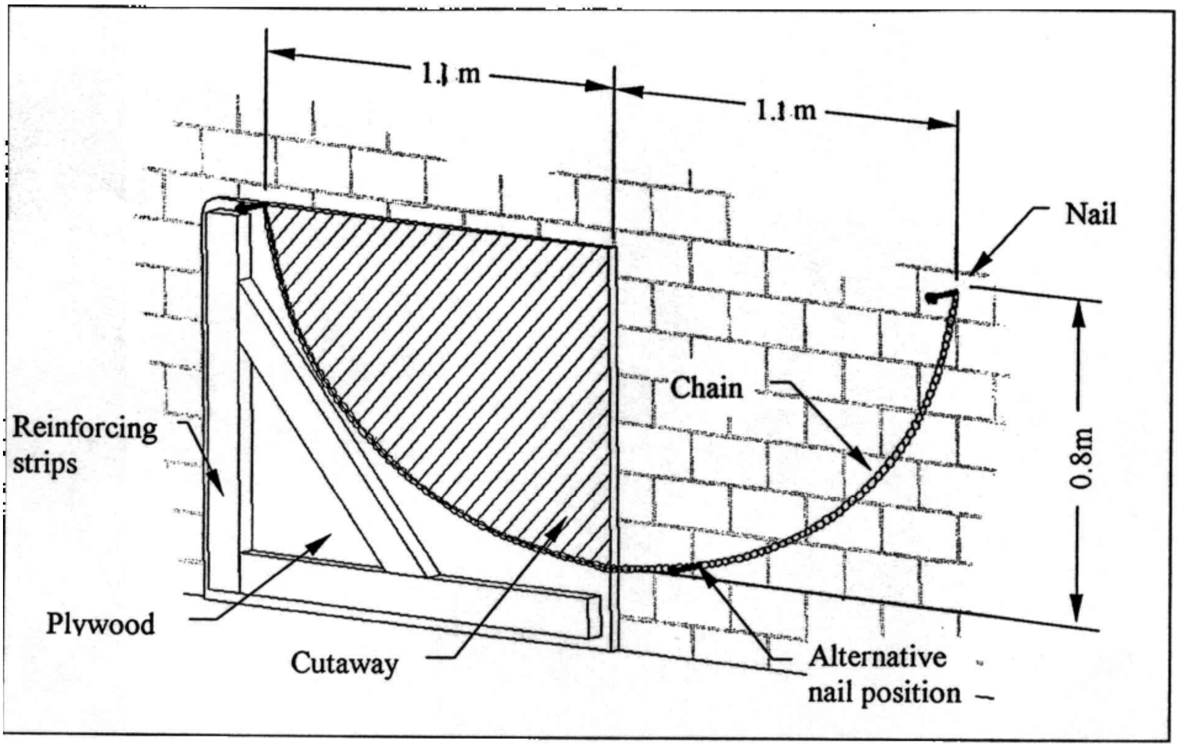


Figure 3 Making the template

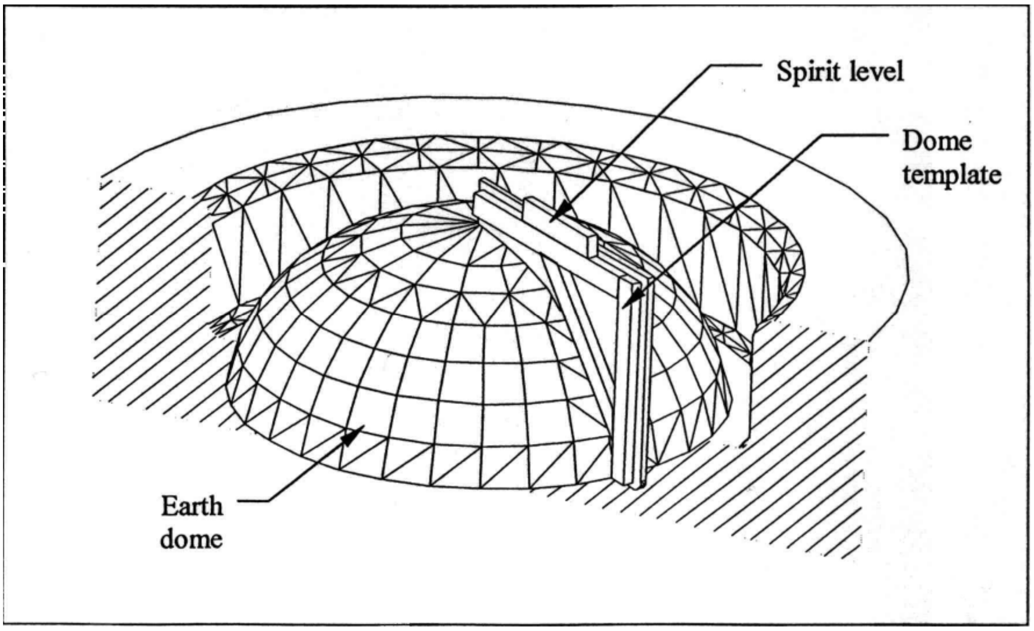


Figure 4 Forming the earth mound

Step 2 Marking out and making the trench and earth mound

The position of the tank should take into account several factors like nearness to the roof, distance from trees and convenience to the water users.

If the roof slopes only one way, as in many shops, a good place for a tank is near the middle of the single gutter or in a corner where two gutters meet. If gutters on both sides of a house have to be used, the tank might go near the middle of a (gable) end wall. Short gutters are easier to hang, can be made smaller and cheaper, and look neater than long gutters. Reducing the distance from gutter to tank reduces the cost of the downpipe. However a tank should not come closer than 50 cm from a wall□s foundations, which means that the centre of the domed cover should be at least 2 meters from the nearest house wall.

A tank might be damaged by a car or heavy cart rolling over it, so it should either be fenced or put where vehicles cannot reach. It is also best if people do not often walk over it.

The tank sticks up only slightly above the ground and is mostly covered with earth. It is not good if during storms, water running across the ground goes over the tank. Roof water is clean, but ground runoff is not and must not enter the tank. So the drainage around the tank should divert such runoff. It should also allow the tank input to overflow - which it will do if it is already full when the rain starts - without washing away the covering earth.

Tree roots are a potential danger: they might penetrate and enlarge a tiny crack in the tank wall. We suggest the tank is at least 10 meters from any large tree and 5 meters from small trees that will not grow large later. It is not always possible to satisfy this condition.

Once the tank position has been decided and the ground levelled, its centre should be marked by a firm and vertical (use a spirit level) thin stake. Make a clear ink mark or cut a ring round the stake about 30 cm above the ground. Using a string 220 cm long looped once round the stake, mark out a circle of diameter 220 cm on the ground. This circle marks the inside edge of the trench in which the ring beam will be cast.

Dig a narrow trench (one hoe's width) outside this circle and throw some of the soil into the centre round the pole. The idea is to dig down 50 cm leaving a mound of firm soil inside the ring rising up to the ring round the stake. The shape can constantly be checked using the template - now with 'TOP' at the top - placed against the stake and rotated like a scraper. The template should be kept level by means of a spirit level and at the right height with its lower corner touching the ring marked on the stake. This is shown in Figure 4.

If the mound is rough or loose or fissured by drying, it can be plastered with more mud and wooden 'floated' to make it smooth and firm.

Chicken mesh can be fixed in the trench so that later on it can be used to improve the joint between the mortar lining the chamber and the mortar of the ring beam. Make a single strip of mesh by cutting a 1.5 meter length into 5 strips each about 18 cm wide and twist joining them end to end - the final strip should be adjusted to fit round the *inside* face of the trench like a ring. This ring should now be folded longwise into the vee-shape shown in Figure 5 and the inside half buried in the earth of the dome. To do this you will have to cut out some earth from the inside of the trench, place the chicken mesh then plaster back the earth again.

The trench is now too wide for the ring beam, so fill back a step 10 cm high round its *outside* so that its bottom becomes only as wide as your foot - about 10 cm. (You will need to walk round this slot when you are plastering the dome). This too is shown in Figure 5. The bottom of the earth dome that faces into the trench should be grooved with a trowel or stick: these grooves will be 'copied' onto the inner edge of the ring beam and will later help 'key' the plaster joint to be formed there.

Finally place the bucket and the basin on the dome as shown in Figure 6. The bucket (the inlet) should be on the side nearest the house, with its edge touching the stake. The large basin (for the excavation access and later the pump hole) should be on the other side of the stake and with its edge 25 cm from the stake. Weight down the bucket and basin with stones and push them into the soil mound so that they do not rock; local excavation will allow the bucket to be sunk a desirable 20 cm into the soil. Put a small fillet of mud round each bowl as shown.

Pull out the stake without disturbing the mound.

*Step 3 Preparing the reinforcing bar*s

Use 6 mm bar; it does not matter whether it is round or knobbly. Make a ring whose diameter is 230 cm, folding over and linking the ends and hammered the link tight so that there is no play in the joint. This ring will take about 8 meters of bar. Test that the ring will sit in the middle of trench without getting close to either its inner or outer edge.

Make two further such rings but much smaller, one each for the bucket and the bowl. Each ring should have a diameter bigger than its bucket/bowl so as to leave a clearance of 3 cm all round it where it enters the soil dome.

Step 4 Casting the ring beam and the pierced dome

The dome and the ring beam that forms its bottom edge are made of strong mortar in the manner shown in Figure 7. The mix is 1:3 (cement : sand) and 2 bags of cement should be ample. Concrete, mixed 1:4:2 (cement : sand : small sharp aggregate), is an alternative where such aggregate is available or can be made; a concrete dome needs only 1.5 bags of cement. (Concrete is more difficult to place as a plaster than is mortar and the surface finish achievable is not so good.) The ring beam is about 10 cm x 10 cm, while the rest of the dome is covered with 2 cm of mortar. However round the bucket and bowl this depth is increased locally to about 8 cm to make a good lip to hold the bucket/bowl and to cover the reinforcing rings there. As usual all three rings of reinforcing bar must be in the middle of the mortar with several centimetres of cover on all sides. So they must be placed as the mortaring progresses. The big ring, in the ring beam, is therefore placed only after 5 cm of mortar is already in the trench.

It is important to check the mortar thickness nowhere gets less than 2 cm as you work up the dome. There should be no joints in the mortar: the whole dome and ring beam should be made (plastered) in a single session with a mix that is dry enough not to slump. As the soil dome may suck water out of the mortar or concrete applied on top of it, it should be thoroughly wetted before plastering the dome starts. Moreover in a hot climate it is wise to do this plastering early in the day so that the new dome can be covered with wet straw before the sun gets very hot.

Step 5 Curing the dome

As soon as the mortar is firm, gently remove the bucket and basin from the top of the dome.

Once the dome is cast it needs to cure under moist conditions for 14 days to develop a high strength. The simplest way to ensure it is kept moist is to cover it with plenty of grass and douse this with a jerrycan of water every morning and afternoon.

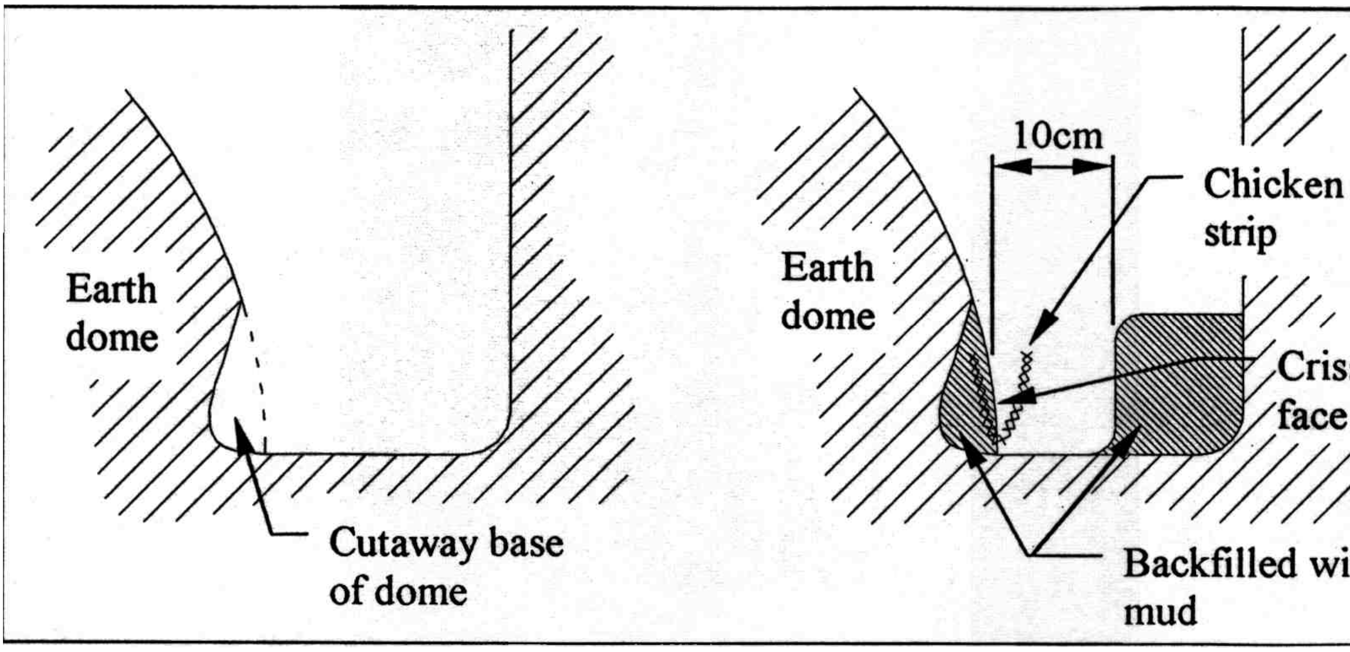


Figure 5 Details of trench (mesh is optional)

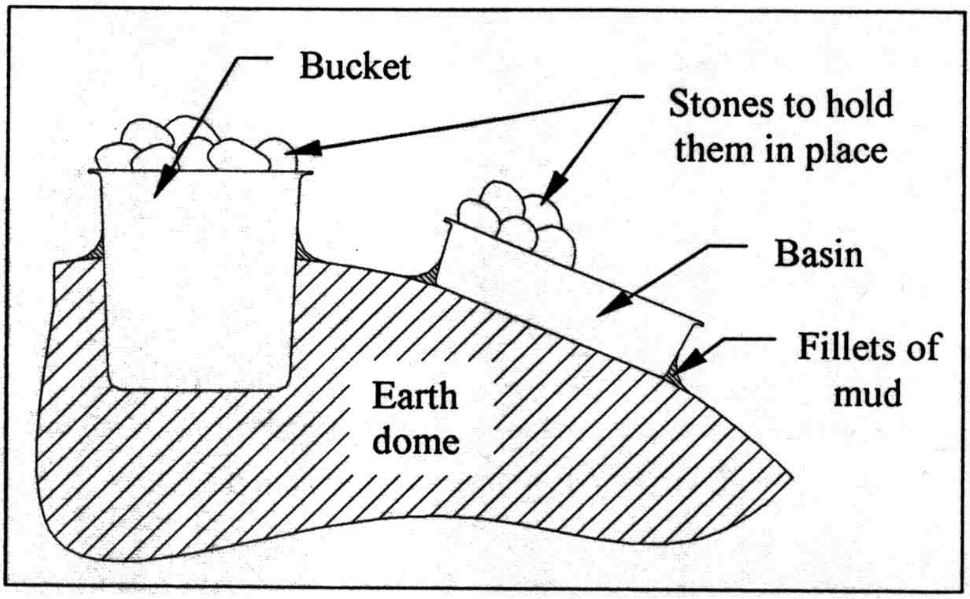


Figure 6 Basin and bucket on mound

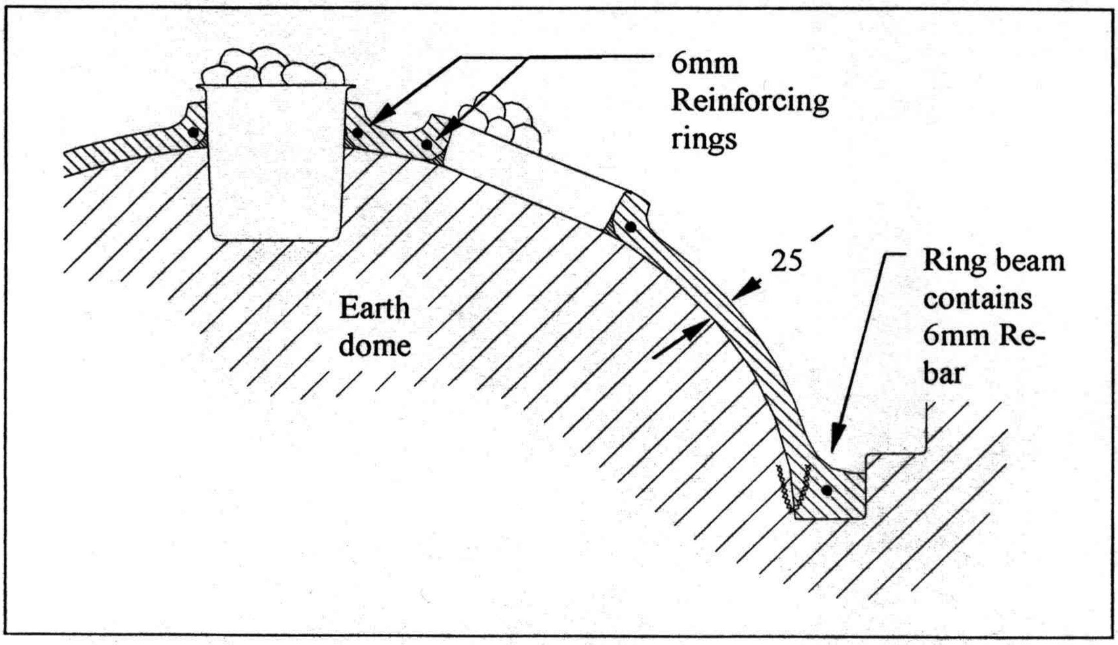


Figure 7 Completed dome

8 Making the Chamber (steps 6 - 7)

The chamber is a dug cylinder with a fully rounded bottom which is lined with mortar to make it waterproof. All the digging spoil has to come out through the two holes in the dome. The chamber must be the right diameter, which is 220 cm, so that it joins properly with the dome and does not undermine the ring beam. It has no corners or sudden changes of direction, since these could be places where the lining mortar cracks.

Step 6 Excavating the chamber

The dome should be strong, but to make sure it is safe it should be inspected for serious cracks. Any big cracks or holes show the dome is a failure and should not be used (because it might collapse while the chamber underneath it is being excavated).

If the dome passes this inspection, start excavating underneath it by reaching through the two holes in the dome. Use the excavated soil to cover the ring beam and lower parts of the dome. When you feel you have dug out enough that the underside of the dome is no longer resting on soil, perform the following safety test. Have 7 people standing close together on the top of the dome. It should not break (as described later under testing, these domes have withstood the equivalent of 25 people□s weight without failing). If it does collapse because of some serious defect in materials or craftsmanship, the people will only fall a short distance and you will have prevented a serious accident later on.

Assuming the dome has passed this test, carry on digging, using the soil to cover the dome up to the edge of the holes. This cover protects the dome from being damaged by heavy objects dropping on it. However during the rest of the excavation make sure there are never many people standing on the dome and that it is not struck by tools. When you lift buckets of soil out through the access hole, take care that they do not strike the underside of the dome on their way up.

Soil is removed until there is room for a person to dig from inside the dome. Then that person digs from inside until there is room for two people.

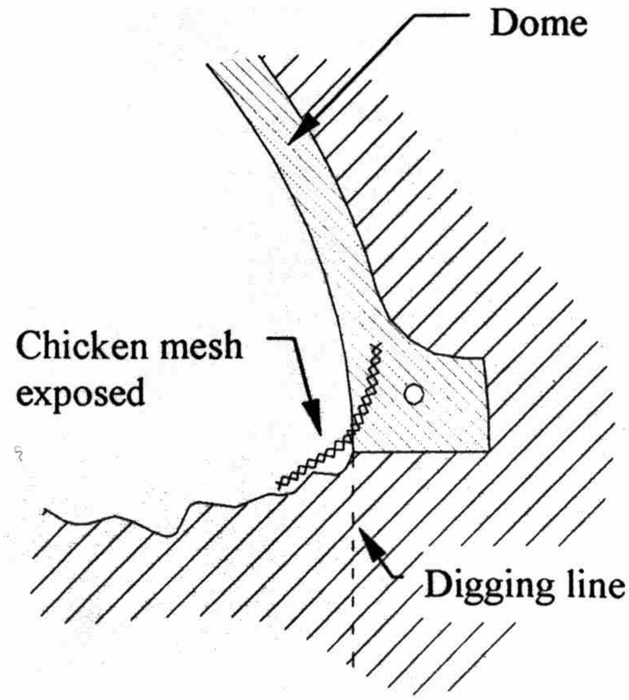


Figure 8 Digging past the ring beam

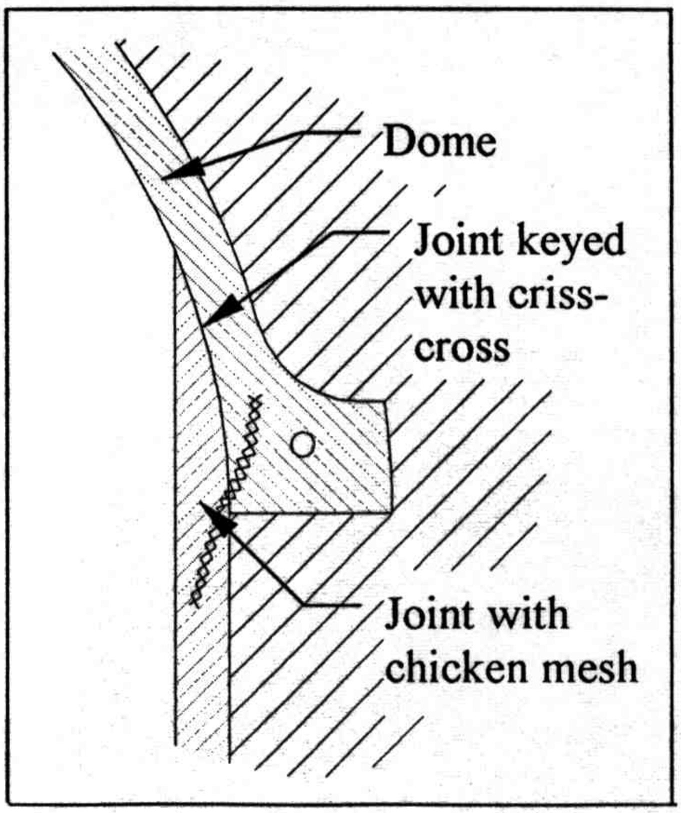


Figure 9 Plastering the pit-dome joint

Digging continues exposing the underside of the dome until the ring beam is reached and the chicken mesh is found. It is most important not to dig directly under this beam because you would be removing the soil in which the whole dome is supposed to be supported. Instead, on reaching the edge of the ring beam you should dig straight downwards as shown in Figure 8.

Soil can be thrown up through the access hole or removed from the pit using a bucket on a rope. The speed of excavation usual depends mainly on how fast you can remove the soil, not on how fast you can dig. If there are two people in the pit, one can dig and the other can keep filling the bucket.

Before the pit is so deep that you cannot easily reach up to the underside of the dome, clean off all the soil sticking to this underside with a trowel then brush and wash it.

The chamber sides are supposed to be vertical, so check them from time to time with a spirit level or plumb bob. It is not necessary to be very accurate. You may come across areas where the soil of the pit sides is loose and powdery, or you may encounter roots. If you do, dig them out and replace with a mortar of firm soil. This is because the mortar lining you will later apply to the chamber sides must be completely supported by them to prevent it cracking.

When the height of the walls has reached the size you want (1 meter for an 8000 litre tank or other sizes as shown in the table on page 9), dig out the base of the chamber into the shape of a round bowl about 1 meter deep.

Once the required chamber size and shape is reached, the final finishing can be done. The soil walls should be scraped smooth, with special care being taken at the edge of the ring beam. All loose soil should be removed from the bottom of the chamber.

Step 7 Lining the chamber

The soil walls are plastered with 2 to 3 cm of ordinary mortar which is finished smooth with a wooden float. The mortar mix is 1:3 and three bags of cement should be ample. The walls need to be plastered in one session so that there are no joints in it. When you reach the ring beam (which is the beginning of the dome) bend down the chicken mesh so that it lies within the mortar. Carry the mortar plaster straight up so that it overlaps the bottom of the dome for 20 cm or more - as shown on Figure 9. The scoring you did in Step 2 will help the plaster overlap to grip. The very bottom of the chamber can be used to store the mortar while plastering the rest of the chamber. This bottom is smoothed last of all, perhaps using the feet of a plasterer who is hanging from the hands of a colleague reaching down through the hole.

This plaster needs curing for 14 days under moist conditions. The walls should be splashed with water every day and the access holes should be covered, to prevent any drying out, for the rest of the time. The chamber walls need finally to be sealed with a paint or "wash" made from cement and water. The walls need to be wetted before this "paint" is applied. 24 hours after this sealing, the cistern is ready to be filled with rainwater.

An alternative technique, reported as being in use for brick-lined tanks in Brazil, is to apply the plaster in two 1 cm coats with a sealing layer of cement wash between them. The first layer should be left rough enough for the second layer to key onto despite the rather smooth cement wash. In Brazil the mortar was made with lime (strengthened with 1 part of cement per 9 parts of lime). In Uganda lime currently costs exactly the same as cement per kilogram so there is no financial saving from using it. However its greater flexibility is attractive if small earth movements are feared. Lime/cement mortar takes over 30 days to cure well.

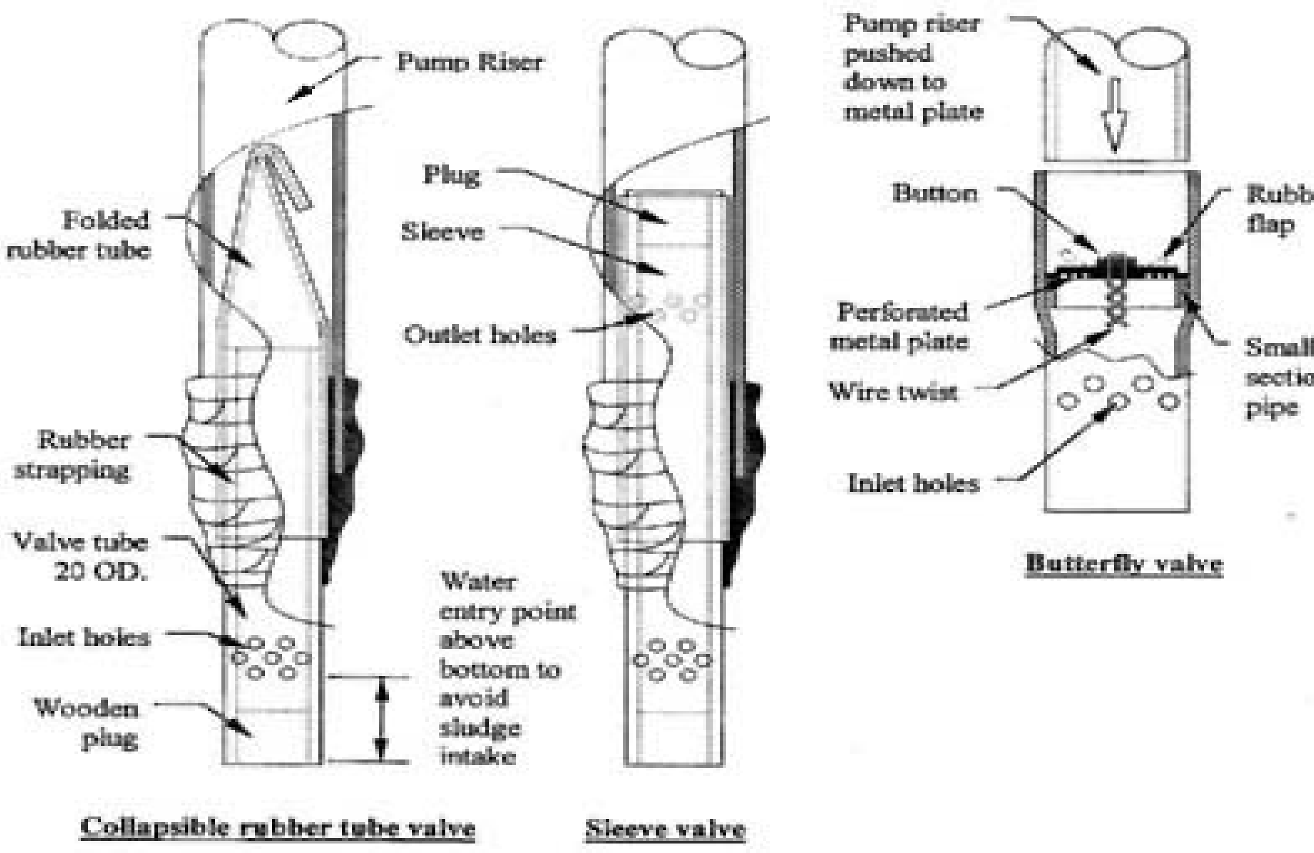


Figure 10 Three designs of foot-valve for a piston pump (wavy line shows riser cut away)

9 MAKING PUMPS (steps 8a and 8b)

Step 8a Making a foot valve

Any piston pump requires a □foot valve□. This is a non-return valve placed near the bottom of the riser pipe immediately above the intake. It should have a low resistance to the upwards flow of water and a high resistance to downwards flow (leakage). As the change-over from upstroke to down-stroke takes only a few milliseconds, the valve should move quickly from its open to its closed position. Delays in doing so will result in lost effort.

Figure 10 shows three designs of foot valve, which we may call □tube□, □sleeve□ and □butterfly□ respectively. All work satisfactorily; each has its merits.

The □**butterfly**□ **foot valve** on the right of Figure 10 is the simplest to make, but when fitted in a small pipe has a rather high resistance to upwards flow. Moreover the extension piece on the bottom of the riser pipe has a larger diameter than the riser itself, which complicates drawing the whole assembly up through the plug in the tank top.

The valve consists of a thin perforated metal disc (for example cut from galvanised steel roofing sheet) covered by a rubber disc (usually made from bicycle inner tube). The perforations in the metal can be made downwards with a hammer and large nail, the top of metal being then hammered and filed flat. The metal disc should have a larger diameter than the inside of the riser pipe but smaller than that of its belled end. The rubber disc is attached along its centre line to the metal by a twist of wire so that it can only flex in the manner of a butterfly□s two wings. It should be large enough to cover all the holes in the metal yet small enough to be able to flex upwards without touching the sides of the riser pipe. A nail with its head cut off, or a long button, makes a suitable bar to restrain the rubber disc.

The metal disc itself sits on a small ring cut off the riser pipe and glued into a socket on a short pipe extension as shown in the figure. It is held in position by the extension being forced up onto the bottom of the riser pipe and jammed there with glue or a slip of paper. A good seal fit is obtained if the metal is heated before insertion, so that it melts into the plastic. The actual socket has an inside diameter equal to the outside diameter of the pipe it terminates. It is formed by pushing/rotating a wooden tool or a soft-drink bottle into the heated end of the riser pipe - a procedure that takes a little practice to do well.

The □**sleeve**□ **valve in the centre** of Figure 10 has a small diameter (e.g 25 mm OD) inner pipe covered by a loose-fitting sleeve of cycle inner tube. The relative sizes of the sleeve and inner pipe are important and therefore need to be matched by trial and error. Too large a sleeve and the valve leaks downwards: too small a sleeve and the resistance to upwards flow is too high. The short inner pipe is perforated at two levels by rings of holes. The lower ring (single or double) is where the water enters; its location determines the clearance above tank-bottom sludge. The upper ring is where the water emerges under the sleeve into the riser. The top of the inner pipe is sealed either by a bung or by heating and clamping flat. For both binding the sleeve onto the inner pipe (below the upper ring of holes) and for jamming the inner pipe into the bottom of the riser pipe, long narrow rubber strips are used. This cheap and useful material, cut from old inner tubes, is sold by bike mechanics throughout Africa. With a little practice it can be used to make firm watertight joints of sufficient strength to resist significant forces.

Unlike the butterfly design, the ‘sleeve’ valve does not require belling of the bottom of the riser pipe, but instead fits within the riser’s diameter. For desludging a tank, the inner pipe can be pushed up higher inside the riser; this forces all water to enter via the very bottom. The sleeve valve is prone to damage by small gravel being drawn into the space between inner pipe and sleeve, so it should be cleaned after use for desludging. Indeed except when desludging it is helpful to bung the bottom of the inner pipe to prevent ingress of tank-bottom grit.

The **‘tube’ foot valve** on the left of Figure 10 is an unusual new design. It requires a permanent fold to be made across a short length of inner tube. Water can flow upwards by pushing the fold open, but when water tries to flow downwards the fold is pressed shut. To make such a permanent fold, the tube must be clamped to create a temporary fold then immersed in a very hot liquid. We have found that brake fluid (for a car) is a suitable fluid. It boils at a much higher temperature than water, so the fold will set permanently if it is placed for half a minute in nearly boiling fluid. Other oils do not work because they attack the rubber. Naturally it helps to make an experiment to fing out the right immersion time. Take care with the hot oil and wait for the rubber to cool before touching it! The folded rubber tube is now tied over a valve tube and the whole assembly is strapped very tightly onto the bottom of the riser pipe. As with the ‘sleeve’ design, it is a nuisance if the inner pipe falls off and lies at the bottom of the tank.

All of these foot valve designs need some care in adjustment. Their performance may be crudely tested by blowing and sucking to detect that there is a difference between their upwards (low) and downwards (high) flow resistance. The latter can also be tested by filling a riser pipe - fitted with the foot valve - with water and checking that the leakage flow does not exceed 1 litre per minute.

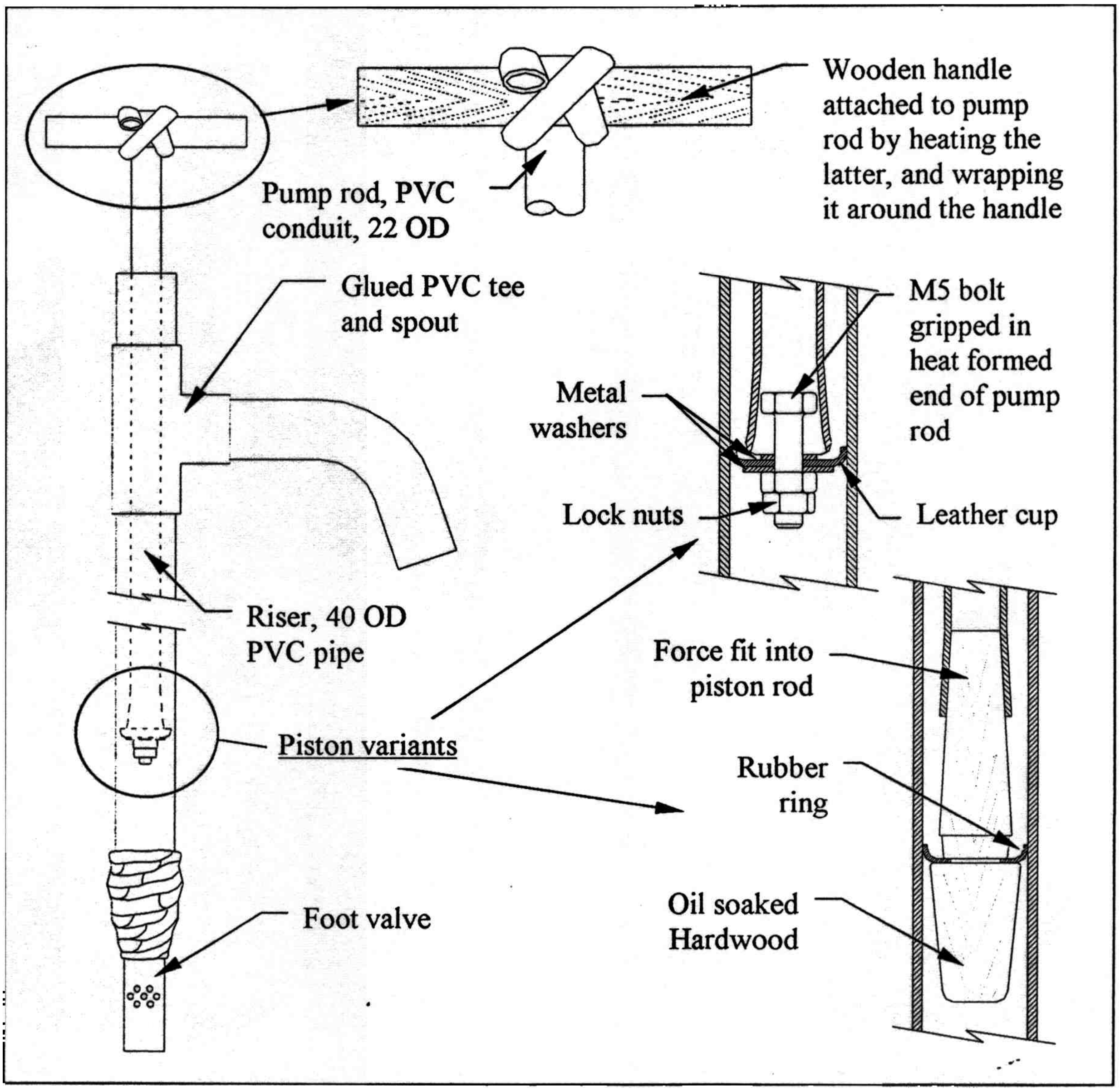


Figure 11 Piston pump with two piston options

Step 8b Piston manufacture and pump assembly

The piston itself must allow water to pass round its edges when it is pushed down, but not when it is pulled up. It therefore requires a slightly flexible skirt. Figure 11 shows two variants. The wooden variant shown bottom right uses a pierced disc of inner-tube rubber to achieve this flexibility. The boiled-in-oil wooden plug (which has a diameter about 3 mm smaller than the riser□s bore) allows the disc to flex upwards but not downwards. The leather variant (middle right) uses a classic □cup□ piston made of leather taken from a motorcycle stirrup pump (bicycle pump pistons are rather too small). Although the cup has some flexibility, it has to fit fairly closely into the riser pipe. Nominal $1^{1}/_{4}$" PVC pipe (40 mm outside diameter) is a suitable size for the riser to use with this piston. There may be other pipe-cup combinations available. The behaviour of leather cups is rather unpredictable. Some wear quickly and some go stiff if repeatedly cycled through wet and dry states. It is helpful to grease the cup. Small cups are usually cheap and available (less than $1 in Ugandan trading posts) and are fairly easy to replace. Note however that the nuts retaining the piston need to be locked together using two spanners/pliers, otherwise they will soon loosen.

The piston rod is made of plastic □conduit□ (made to guide electrical wires through concrete floors) whose outside diameter is commonly 22 mm. Conduit is cheap but not very stiff. It can be given extra stiffness by pushing a 6mm steel reinforcing bar down it or filling it with mortar. Such stiffening is however not essential. When heated such conduit can be easily moulded. For example it can be pushed hot over the end of the wooden plug of the first piston variant or crimped round the head of the bolt to which the cup piston is fixed. It can also be wrapped hot like a flat strip round the pump handle (Figure 11 centre top) and held in position until cool. The ideal diameter of the piston rod is 70% of the riser□s bore. This gives an almost steady flow from the pump - the delivery flow during the down-stroke is the same as during the up-stroke. Other diameters between 50% and 80% are acceptable. The length of the piston rod should allow the piston to approach within 2 meters of the top of the foot-valve. If the rod is too long there is a danger of hitting the foot-valve. If it is too short the pump may be hard to get started (□self-prime□), especially if the flexible skirt of the piston is worn or if the pump is used at places very high above sea level. Priming is quickest if long strokes are used until water appears at the spout. Calculations (see Table below) show that if the piston at its lowest position is 2 meters above the water level in the tank, then even with a perfectly sealing piston priming requires a stroke length of at least 0.1 meters. If the piston leaks a bit this stroke length needs to be significantly longer. Once a piston pump is primed, however, short strokes can be used.

The pump needs a spout. PVC □tee□ connectors make the simplest way of joining the spout to the riser providing PVC cement is available. An alternative to cement is to wedge the pipe into the tee with a layer of paper and reinforce with rubber strip wrappings.

TABLE OF MAXIMUM SUCTION HEADS ASSUMING PERFECT PISTON SEALING
(suction head = height of bottom point of piston stroke above the water level in the tank)
(compression of air during priming down-strokes is assumed adiabatic, with $\gamma = 1.2$)

Stroke of piston		0.1 m	0.2 m	0.3 m	0.4 m	0.5 m	0.6 m
Altitude	**Pressure**	**Maximum Suction Head in meters**					
Sea level	1.0 bar	2.1	2.85	3.5	3.95	4.35	4.7
+ 800 m	0.9 bar	2.0	2.7	3.3	3.7	4.1	4.4
+1600 m	0.8 bar	1.85	2.55	3.1	3.5	3.85	4.15

10 Completing the Cistern

Step 9 Setting the pump in position

The pump riser penetrates the top of the tank via a mortar plug made to fit the larger hole in the dome (the plug is moulded with the same basin as was used during dome construction and sealed into position with mud). The plug carries a sleeve (see Figure 12) through which the pump riser passes, which should be angled so that it points at the tank bottom. Heavily scratching the outside of the sleeve should be sufficient to make it bond to the concrete. For an even better bond a strip of pvc - cut from the riser piping - can be glued onto the outside of the riser where it passes through the plug.

With any piston pump, significant downwards *and upwards* forces are transmitted into the riser from the pump handle. In consequence the riser needs to be held firmly in the sleeve. Downwards movement can be resisted by using a rubber-strip wrapping on the riser that jams into the top of the sleeve. Some adjustment is usually needed to ensure that the intake pipe of the foot valve reaches the tank bottom at the same time as the riser jams tightly down into its sleeve. Resting on the bottom in this way ensures the foot valve does not get pushed out during a down stroke. Upwards movement of the riser can be resisted by wiring the spout tee down to the lifting handles of 6 mm reinforcing bar set into the plug.

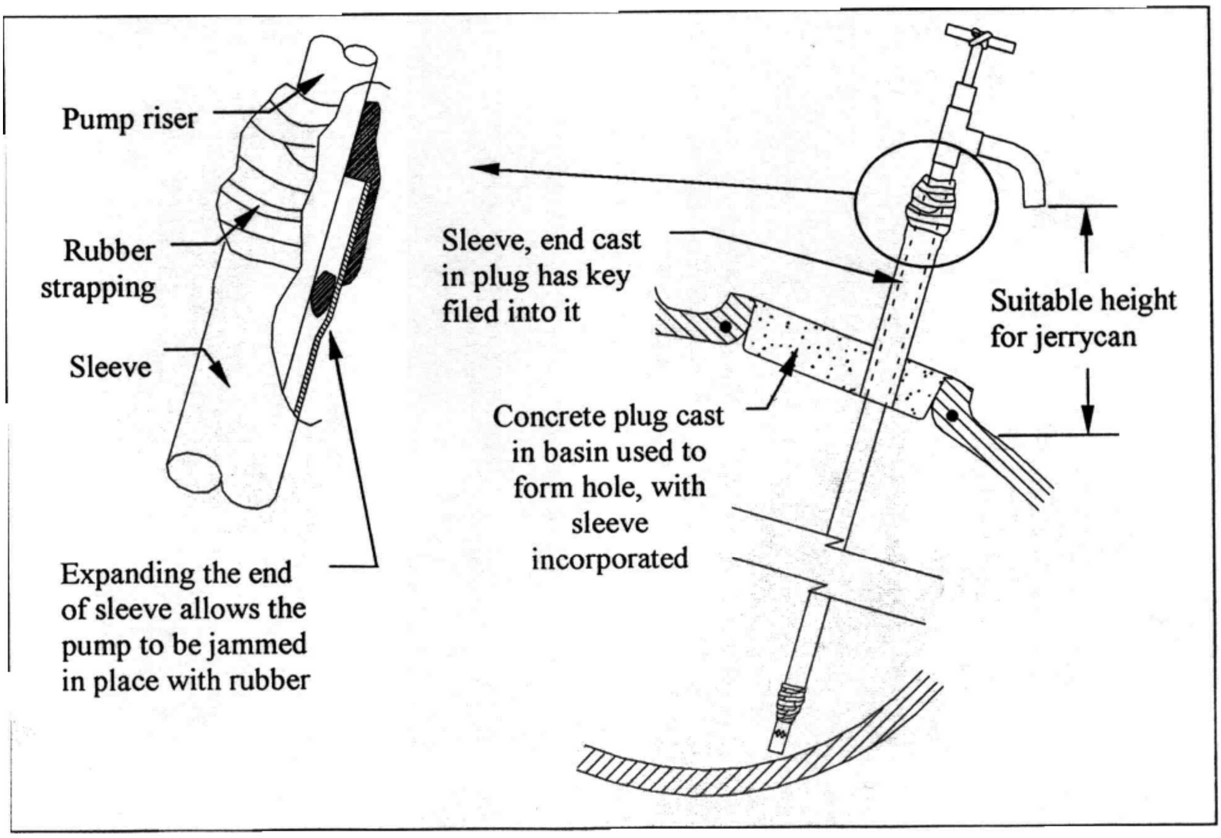


Figure 12 Fitting the pump to the tank

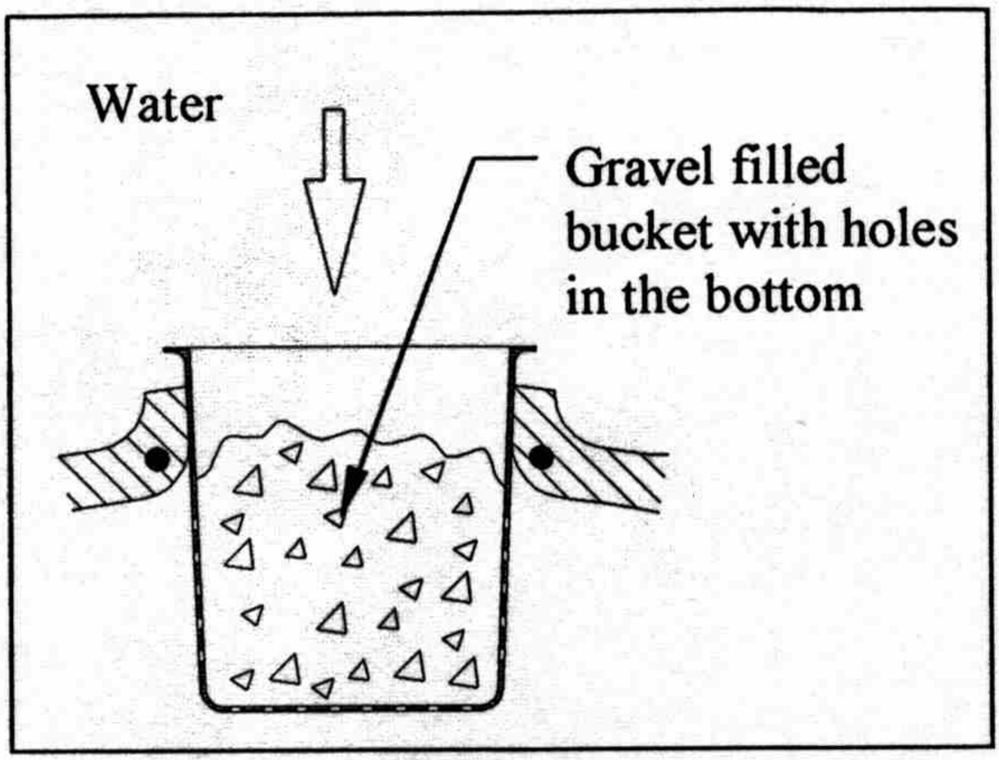


Figure 13 Water inlet filter

Step 10 Making the inlet filter

Water enters the cistern rapidly during heavy rain. The inlet should be able to handle flows up to 120 litres per minute (e.g. 4 mm/minute falling on 30 m^2 of roof) without overflowing. At such high flowrates only coarse inlet filtering is usually possible, namely the prevention of twigs and leaves from entering the cistern. The inlet to the cistern should also meet the criteria of excluding light, being inpenetrable to mosquitoes, not presenting a danger to children, preventing the inflow from stirring up any sediment in the bottom of the chamber and being able to handle cistern overflow. Any material retained by a filter (or by a sedimentation chamber) must ultimately be removed from it, so ease of cleaning is also desirable.

One inlet design that meets these various criteria is shown in Figure 13. The bucket is the same one that was used to mould the inlet collar in *Step 2* and should therefore fit closely into that collar. Being set low, little of its exterior is exposed to sunlight and hence UV degradation. The primary filtration mechanism is a coarse cloth stretched over its top and tied under the bucket's edge - this can be removed for back-washing. A gravel filling to the bucket weights it down, reducing the chance of its removal by children. It also supplies back-up filtration in case the cloth is missing or torn, it excludes light and it prevents a heavy inflow from splashing out again. The bucket should be pierced in many places, in its base and the lower part of its sides, by holes whose total area should exceed 20 cm^2. 80 holes of 6 mm diameter should suffice to carry the peak flow without the bucket overtopping. The presence of so many holes means that within the cistern the inflow becomes a spray rather than a downwards jet. Such a spray does not stir up the cistern contents as a free-falling jet might. Of course the gravel must be larger than the holes in the bucket.

Should the cistern be already full when it rains, the inlet bucket will overflow. Its 'spout' (formed by heating if not initially large enough) should direct this overflow to the drainage provided for spillage from the pump or the collecting vessels.

Step 11 Making the hard standing and drainage

Below the spout of the pump (itself of height suitable for the collecting vessels in local use) there must be easily cleanable 'hard standing' for both the collecting vessel and for the person pumping. This hard-standing requires proper run-off or drainage provision, so that puddles do not form for mosquitoes to breed in and the soil covering the edge of the dome does not become saturated. A proper soakaway, situated well outside the cistern's ring beam may be needed , but often the slope of the land enables a simple channel to suffice.

11 POSSIBLE FAILURE MODES

We might divide 'failures' into 'dangerous failures' (DFs) that threaten human life, 'total failures' (TFs) that require the cistern to be abandoned and 'partial failures' (PFs) requiring repair or degrading the cistern's performance.

Dangerous failures include:

DF1 inwards collapse of the dome during excavation of the chamber or later during tank use,

DF2 significant ingress of polluted surface water or of latrine effluent,

DF3 providing a breeding ground for mosquitoes close to a dwelling, DF4 children falling in and drowning.

DF5 collapse of the chamber during digging.

Failure DF1 is not easy to design against because the forces on the dome are imperfectly known in size and direction. The dome shape (catenary) is the optimum to resist its self weight and good for resisting top loading. It is less good for resisting outwards pressure forces when the tank is completely full, but any failure they could cause would not normally be □dangerous□ so is discussed under PF1 below. The simple test mentioned in *Step 6* should identify major dome defects, while the test programme described in section 12 below indicates a satisfactory safety factor. Attempts will be made during 1997 to apply complex computer finite element methods to analyse this □shell□.

Failure mode DF2 is combated by the raising of the inlet collar above likely surface flow levels, the sealing in (usually with clay) of the mortar plug to the access hole, keeping the cistern well apart from latrines and not digging below the rainy season water table.

Failure mode DF3 is avoided if the inlet filter is properly made. and the spillage drainage is adequate.

Avoidance of failure mode DF4 depends upon care by the household owning the cistern; design features can never totally remove the need for social controls like forbidding children from trying to swim in a cistern. Weighting the inlet filter bucket and sealing the access hole plug will normally be sufficient for DF4 avoidance, but fencing off the cistern area would add extra safety for babies.

To avoid the possibility of DF5 collapses, shoring the chamber during its excavation would be required by some countries□ building safety codes. This would significantly increase the difficulty of both excavating and subsequent rendering the chamber. Where deep latrines are already normally dug without shoring (e.g. as in the trial country, Uganda), excavating the significantly shallower cisterns should incur no danger.

Possible catastrophic failures are

TF1 cistern collapse during earthquake

TF2 slumping or other movement of the soil walls of the chamber to the extent that the chamber lining becomes unsupported and cannot contain the water pressures

TF3 an empty cistern □floating□ out of the ground.

Until further experience is gained, avoidance of TF1 requires that these cisterns are not built in seismic zones. In fact some of the prototypes have survived minor tremors and one has been deliberately built in a seismic zone to test its durability there.

Because of the possibility of TF2, wall slumping, the construction technique described is not suitable for loose sandy soils, highly expansive clay soils or areas where the water table sometimes rises within say 3 meters of ground level.

Avoidance of TF3, flotation, also requires that the water table does not rise higher than say 0.7 meters above the bottom of the chamber. Fortunately it is very unlikely for a cistern to be empty following rains heavy enough to raise the water table so high.

Partial failures include:

PF1 cracking in the dome

PF2 localised cracking of the chamber lining leading to leakage

PF3 ingress of tree roots

PF4 heavy sedimentation leading to pump blockage or loss of storage capacity.

Serious cracking of the dome, PF1, due to water pressure could result in leakage resulting in effective loss of about 1000 litres of capacity. As it is undesirable for the dome mortar to anywhere go into tension, the inwards forces due to soil loading should largely (or even completely) counterbalance any outwards water-pressure forces. Even dry soil has a higher density than water, so this condition is usually satisfied. In fact mortars and concrete should be able to carry tensile stresses up to say 0.5 MPa. In the absence of four features (ring beam tension, dome taper, dome self-weight and overburden weight) the maximum tensile hoop stress due to water pressure could reach 80 kPa x $D/2t$ = say 4 MPa, where D is the dome diameter and t its thickness.. This is considerably more than the tensile strength given above. The presence of each of the four features however significantly reduces the hoop stress.

Localised chamber cracking, PF2, could lead to loss of all water. Outward leakage under the ground may be difficult to locate. Once a leak has been located, however, repair is straightforward as the cistern can be entered to cut out and re-render cracked walls or to apply another cement wash.

Tree roots, PF3, are attracted by minor leakage or may reach the chamber even without such leakage. Live roots in a tank are a initially a minor nuisance until they become numerous or exacerbate cracks by their expansion. Dead roots may rot, creating leakage paths and possibly de-oxygenating the water. Roots can be detected and initially trimmed during annual cleaning. In time they will require cutting back and local replastering.

Sediment is often present in roof run-off and needs periodic removal (PF4) . This can be done by entering the tank or perhaps by sluicing while pumping out.

12 TEST RESULTS: LEAKAGE, DOME STRENGTH, CHAMBER FLEXING, PUMP PERFORMANCE

Leakage tests

Three tanks were built in early 1996 at Kagadi. None showed serious leakage by early 1997. One was cycled (full/empty) a number of times and tested for leakage after each filling. The water loss rate averaged 3.6 litres per 24 hours. Further leakage tests on these and on four further tanks completed in March/April 1997 will be carried out when the overdue March rains have filled them. However leakage is not easy to measure - to demonstrate that leakage is under 1 litre per day requires measurement of water level changes to a resolution of 0.2 mm/day. Such precision is not possible under field conditions. Indeed it is difficult to guard a tank against being used for as long as 24 hours. In practice a leakage of up to 5 litres/day (1 mm/day) would be acceptable and this rate of level change is just measurable without special instruments. As 1 mm/day is less than the evaporation (typically 6 mm/day) from an open tropical water surface, it is important that measurements are made with the tank well covered so that the air above the stored water is at 100% relative humidity. Even where this is done, it is found that the level of a newly filled cistern may *initially* fall at over 1 mm/day even though it subsequently stabilises. This initial fall may be due to evaporation to saturate the air in the cistern, absorption by the wall plaster or soil movement .

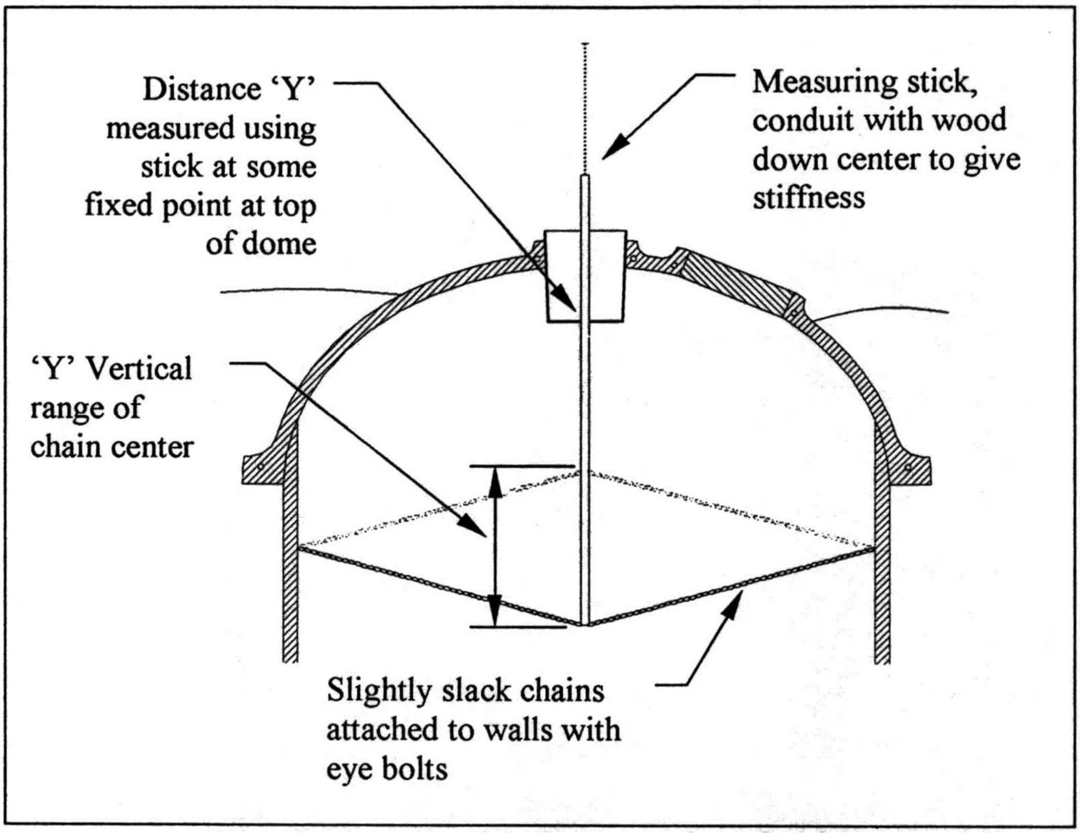


Figure 14 Testing the expansion of a cistern

Dome loading tests

We are of course interested in the integrity of the dome: sudden dome failure during construction or later could endanger lives. The dome is subject to the following forces

(a) its own weight of about 300 kg

(b) the weight of builders or users standing on it, say 6 x 60 kg

(c) the weight of soil placed upon it (typically 800 kg, mostly acting close to the outer edge of the dome)

(d) water pressure acting outwards when the cistern is completely full.

The last two forces are to some extent counteracting, both being generally perpendicular to the local dome surface, with the soil pressure acting inwards and the water pressure outwards. Inwards forces compress the dome to which forces it has a high compressive strength, while outwards forces lead to hoop tensions to which it has poor resistance. Neither of these forces impinge on the central part (i.e. the top) of the dome whose failure would be most dangerous.

The first two forces act downwards and are translated into compressive stresses in the mortar by the dome's catenary shape. It is these forces that might collapse the top of the dome inwards.

Two domes were therefore subjected to large downwards forces in the central part by loading them with bricks. It proved necessary to mortar a locating ring of bricks onto the dome, about 300 mm above the ring beam, to prevent the column of test load bricks slipping off the curved dome surface. Thus the test load was applied approximately uniformly over a circular area of diameter 1900 mm (to be compared with about 2250 mm for the dome's junction with its restraining ring beam) corresponding to 70% of the dome's plan area. The test column of bricks was assembled in a way that encouraged transmission of its weight along paths through the dome□s shell rather than directly to the locating ring.

Using all the bricks (and people□s weight) available, loads of 1500 kg and 1700 kg were applied to the mortar and concrete domes respectively. Both domes were 20 mm thick. Following normal civil engineering practice, the maximum expected dead and live loads (namely loads (a) and (b) above) were multiplied by factors of 1.4 and 1.6 respectively, giving a design load of 996 kg. Thus including a self weight of 300 kg, the test loads represented safety factors of 1800/996 = 1.8 and 2000/996 = 2.0 respectively.

Neither dome showed any signs of cracking. Although the test were rather crude, they give reasonable confidence in the design.

Chamber Flexure Test

The chamber walls consist of mortar against undisturbed soil. Concrete or mortar is usually assumed to be able to tolerate a tensile strain of not more than □100 microstrain□ (0.1%). Tests were undertaken with two chambers to measure their expansion when filled with water and therefore check if the circumferential strain was excessive. Arrangements to measure variations in mid-height diameter due to variation in water pressure were made in both chambers. The measurement was not simple since a resolution of less than 1 mm is required and the measurement points are inaccessibly submerged. Slightly slack chains (see Figure 15) were stretched between eye bolts in facing walls of each chamber and the vertical ranges of the chain centres were measured. This range y is the distance between the highest point to which the chain centre can be pulled up and the lowest point to which it can be pushed down. Tensions in the chains were kept low and repeatable, so that variation in chain lengths were negligible. It can be shown by Pythagorus theorem that movement in the walls that increases the chamber diameter by x will reduce the vertical range from y_1 to y_2 where $x \approx (y_1^2 - y_2^2)/2L$. L is the length of the chain, very nearly equal to the chamber diameter of 2200 mm.

By pumping water back and forth between two cisterns of approximately equal size, the following results were obtained after 2 days of pumping. (Note that $2L$ = 4400 mm.)

Description of cistern	□A□ - height = 2850 mm			□B□ - height = 3200 mm		
Variable	state	water depth/mm	y/mm	state	water depth/mm	y/mm
Values at 1130 on 21/3/97	full	2160	305	empty	450	235
Values at 1830 on 21/3/97	empty	1180	306	full	1330	239

Values at 0930 on 22/3/97	empty	810	316	full	1490	234
Values at 1730 on 22/3/97	full	2100	310	empty	250	235
$(y^2_{max} - y^2_{min})/4400$	1.55 mm (equiv. to 706 PPM)			0.54 mm (equiv. to 243 PPM)		
$(y^2_{mean\ empty} - y^2_{mean\ full})/4400$	0.49 mm (equiv. to 224 PPM)			0.16 mm (equiv. to 73 PPM)		
Mean change in water depth	1135 mm			1060 mm		

While more results would give greater statistical confidence, in the face of a measurement uncertainty in *y* of up to 2 mm, it seems that the soil walls are successfully supporting the mortar lining, since the strain in the mortar plaster is probably under 250 PPM. Strains over 100 PPM may produce fine cracks but the curing conditions are so good and the mortar is worked so dry that these should not be serious. Reinforcing may be desirable to prevent concentration of strain onto a few large cracks.

Pump Testing

Pumps need testing for their performance and their durability. The first is straightforward and has been done at Kagadi and at Warwick University. The latter is laborious and uncertain (in the absence of large experimental samples) but has been commenced at Kagadi. Cistern pumps are being installed alongside the main metal pump on a shallow well that is very heavily used (50,000 litres per day) and has long queues. This duty is much more onerous than pumping from a household cistern and therefore represents accelerated testing.

Laboratory tests with the piston pump using either piston variant showed that over 15 litres per minute could be raised from a depth of 4 meters using moderate effort. Brief field tests with both variants of piston lifted 27 litres per minute from 2 meters. The wood and rubber piston sometimes unrolled when used in a dry riser: the rubber needs to locate tightly on the wood to prevent this from happening. Wiring down the pump onto the concrete plug, as described on page 22, gave it a better stiffness and pumping feel. The tube type footvalve has not undergone any field trials: the other two have.

13 COSTS

The current costs of producing cisterns and pumps may be divided into costs of materials and labour on the one hand and the cost of □management□ on the other. Set out below are materials and labour costs based upon conditions in rural Uganda in 1996-7 and converted to US dollars at a rate of $1 = USh.1,000. Certain items like sand and unskilled labour may be provided by householders outside the monetary economy although of course they still incur costs and may indeed also raise actual monetary supervision costs.

Cistern costs (8,000 litre capacity with 20 mm dome and 2-coat chamber lining)

Item	*Quantity*	*Cost / $*
Cement/lime (including transport)	250kg	65
Sand (assumed from a nearby source)	18 wheel barrows	3
6 mm reinforcing bar	12m	5
Chicken mesh	3 m^2	4
PVC Bucket + 0.5 m of 50 mm piping		3
Unskilled labour for digging (9 m^3) etc.	20 person days	40
Plastere	2 person days	8
Supervisor + say 25 km travel	1 person day	10
Tools		(say) 5
	TOTAL	**143**

Pump costs

Item	*Quantity*	*Cost / $*
50 mm OD medium PVC pipe	0.5m	1.2
40 mm OD medium PVC pipe	4m	8
25 mm OD heavy plastic pipe (nom $^3/_4$" bore)	0.3m*	1
20 mm plastic conduit tubing	2m	2.5
40 mm PVC tee and a piston	1 off*	2.8
Manufacturing labour	0.5 day	2
Wire, PVC cement, rubber, wood		1
	TOTAL	**18.5**

Notes: * Piston pump assumed to have sleeve type foot-valve & leather cup piston

TOTAL for CISTERN + PUMP $160

14 CONCLUSIONS, DESIGN VARIANTS AND FURTHER WORK

Conclusions

Under favourable soil and meteorological conditions and where the cost of labour for digging is low, the cistern design described above seems capable of bringing all-year domestic rainwater harvesting within the financial reach of many rural households. It has been developed for Ugandan conditions where it may cost around $160 to produce (for 8000 litres storage capacity and including a hand pump). This is substantially less than the alternatives available in that country. The design is likely to find some application in other countries close to the Equator, and in urban as well as rural situations.

The cistern relies on the support of the soil in which it is dug. It is not normal practice to assume such support, so the design may be regarded as somewhat risky. The limited field evidence to date suggests that the risk is not severe. The three tanks already in use for over twelve months are performing satisfactorily. The tests already performed on two of them indicate low initial leakage, little wall movement under cyclic water loading (under 250? PPM strain) and a safety factor of 2 over a pessimistic design load for the covering shell (dome).

In the absence of a suitable commercial pump, two designs of hand-pump have been developed to meet a particular performance, maintenance and (low) cost specification. These have performed satisfactorily in the short term but their durability is not yet determined.

Design variants

Some design variations have been discussed in this paper.

The dome of the tanks built in 1996 were 25 to 30 mm thick. Those recently tested for strength were 20 mm thick and performed well. 20 mm will be used henceforth as a norm. Moreover both mortar and concrete have been used for the dome. Concrete uses less cement, but requires fine aggregate (which is not widely available in rural areas) and is much harder to work smoothly as a plaster. There is some danger that these workability problems could lead to serious cracks in inexperienced hands. The mortar dome looks better. Mortar is more vulnerable than concrete to shrinkage during curing, but this should not matter in a largely unconstrained dome. On balance we recommend mortar despite the 33% higher cement requirement.

The chambers of the 1996 cisterns were single plastered to a thickness of 30 mm. The later tanks are using 20 mm applied as two layers (e.g. 15 mm plus 5 mm) rather than one. The tank most in danger of earth tremors has just been plastered with a 2-layer lime-cement mortar; it may take some years before the benefits of using this slower curing but more flexible plaster can be assessed.

The piston pump appears to be easy to use but its durability is not well tested. Both piston variants and all three foot valve designs seem satisfactory.

A variant of considerable interest to users is a much bigger cistern - say one of 20,000 litres capacity. This could be used with institutional roofs like those of schools and churches. Such a cistern must either be very deep (e.g. 7 meters) or wide. A diameter of 3 meters (40% more than current designs) and a depth of 4 meters (dome top to chamber bottom) would give adequate capacity. Almost certainly a 30 mm dome of this span would be safe, so such a large tank looks feasible.

Further work

Further leakage tests, performed on a number of tanks, are underway. They should increase confidence in the design and may lead to exploration of repairing cracks or giving tanks a further cement wash. Theoretical modelling of both dome and chamber may indicate the need for a modified construction procedure - such as filling a tank during its curing period to 'pre-stress' its lining. The uncertainty about the forces generated by the undisturbed chamber walls and by the back-fill over the dome makes such analysis of limited value.

Depending upon the outcome of funding discussions, tanks and pumps may be built in several of Uganda's 40 Districts during 1997, in order to check their local costs, construction time and performance. Other desirable further work concerns the development of 'ancillaries' such as a very cheap water-consumption gauge and an 'in-tank' slow sand filter.

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