Engineering Undergraduate Project

Development and Selection of Low Cost Handpumps for Domestic Rainwater Water Tanks in E. Africa

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Summary

This report gives details of the development and selection of a handpump suitable for use with domestic rainwater harvesting tanks in East Africa. The objective of the project was to develop a small low cost handpump, which can be manufactured, maintained and repaired with a minimum of tools and skill and that the materials can be found in most local hardware outlets and markets.

Four designs were proposed which were selected from a range of pump technologies for low head and low flow rates. From these, two were selected for their ease of manufacture, low skill level and expected reliability. The two handpumps ('Harold' and the 'Enhanced inertia') were subjected to a series of performance and durability tests. From these tests, both handpumps were found capable of lifting at least 15 litres per minute at 70 cycles per minute with acceptable hydraulic efficiencies. The actual lifting rate was significantly greater than the value given in the specification.

The durability tests showed very little evidence of wear in either handpump after 145 hours continuous running other than some potential splitting in the valve surfaces. An extended endurance test on the recommended handpump, the Enhanced inertia, resulted in it lifting around 300,000 litres and having an equivalent life of 8 years.

The handpumps were produced in Uganda for less than $10 for a 3.5m length, which was one of the main criteria in the specification. The pumps were successfully manufactured by a number of technicians in Uganda after a two-day training workshop and this illustrates that the design and technology is appropriate.

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Glossary

CATRL	Consumer’s Association Testing and Research Laboratory
DRWH	Domestic Rainwater Harvesting
DTU	Development Technology Unit
GBP	Great British Pound
lpcd	litre per capita day
NGO	Non governmental organisation
PAT	Portable electrical Appliance Test
PVC	Polyvinyl chloride
UGS	Ugandan shillings
UNICEF	United Nations International Children Emergency Fund
URDT	Ugandan Rural Development & Training organisation
WHO	World Health Organisation

1. Introduction

The aim of this project was to develop a suitable small low-cost handpump, which could be used for abstracting water from Domestic Roofwater Harvesting (DRWH) systems in East Africa. A low-cost DRWH system is shown in Figure 1, and consists of a roof to intercept the rain, a series of gutters and downpipes, and a purpose built tank into which the handpump is installed.

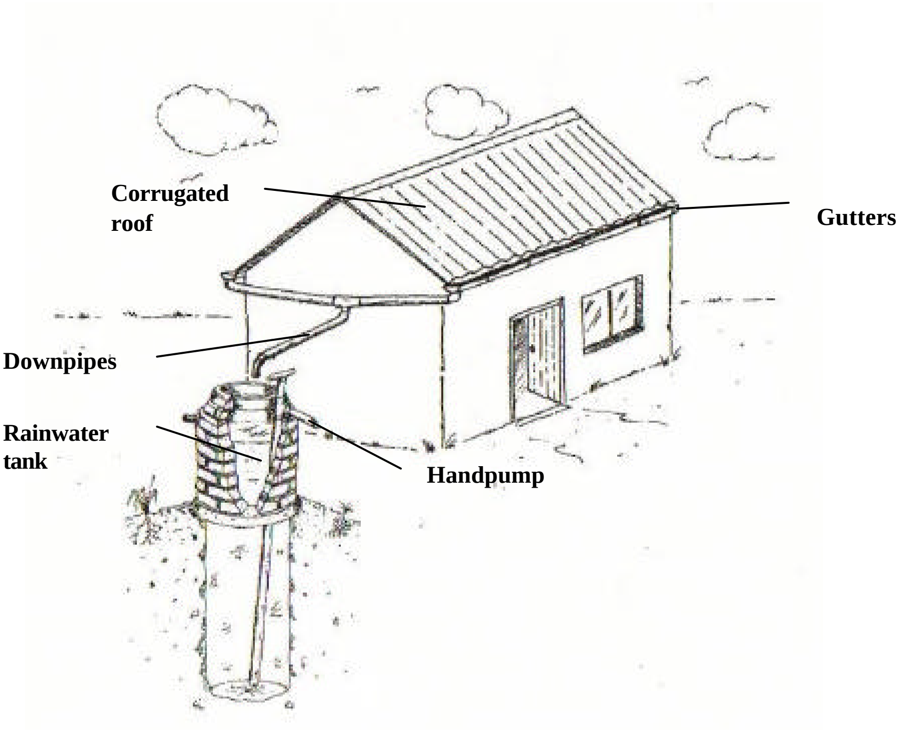

Figure 1 A domestic Rainwater harvesting system

This project was divided into two phases. Firstly an introductory phase, carried out in Uganda (chosen to represent African conditions), was used to identify constraints within the environment and expose four handpump designs to users. Secondly, the main phase of the project was to identify two candidate designs, refine them and carry out performance and endurance tests at the University of Warwick.

One of the main priorities in developing the handpumps was to ensure that the manufacture and materials could be made and/or sourced from within the local area.

The first phase was carried out by the author in Mbarara, (the fourth largest town in Uganda), during July/August 2000 and at Kyera farm, Mbarara. This involved assessing the manufacturing capabilities within the locality, material supplies and the availability of tools in local markets. Some prototype handpumps were manufactured and installed in DRWH systems in Uganda.

Many existing pumps may be regarded as over designed and too expensive to incorporate in to a DRWH system. They can also be difficult to maintain because of the high cost of spares, and the spares may be stocked some distance from the pump location.

The second and main phase was carried out at the University of Warwick. This involved choosing two of the four proposed designs and carrying out a series of performance tests, refining them and then subjecting each handpump to an endurance test.

To achieve the aims and objectives of this project, a plan was set out so the project could follow a logical sequence of tasks over the allocated period and finish completed on time. A software package was used to plan the projects tasks, this was then used to monitor the progress of the project and make adjustments should any arise. A hard copy of the project plan is shown in Appendix 1.

2. Analysis of need and development of specification

Many areas of East Africa have a very varied rainfall pattern and in particular regions, for example in Rwanda, this can result in a six-month dry season. Many rural families do not have access to an adequate and safe water supply. This can mean long treks to some distant water source, which may be of low quality and consume valuable hours from their daily duties.

Fetching water may often involve many hours a day in walking several miles to and from the source by either children or women. The time spent collecting water is a double burden, as it means less time is available for the productive activities on which subsistence economies depend[1].

Definitions given by WHO (1996[2]) are as follows:

- Access to water: In urban areas, a distance of not more than 200 metres from a home to a public standpost may be considered reasonable access. In rural areas, reasonable access implies that a person does not have to spend a disproportionate part of the day fetching water for the families needs.
- Adequate amount of water: 20 litres of safe water per person per day.

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[1] Water Supply and Sanitation programmes, DFID

[2] WHO, catalogue of Health Indicators. Geneva.

- Safe water: Water that does not contain biological or chemical agents directly detrimental to health.

46% of the rural population of Uganda for example does not have access to safe water (UNICEF).

To ease the burden of the above points, a DRWH system, which incorporates a handpump as shown in Figure 1, can be used to supplement a household's daily need during this dry season.

2.1 *Specifications*

The following specification has been drawn up to represent the particular conditions under which a handpump will be used:

- The handpump must be of low cost (i.e. affordable by low-income households in Uganda, with a maximum cost of UGS 18,000 ≈ $US10).
- It must be possible to manufacture and maintain the handpump within E. Africa at village level with a set of basic hand tools.
- The handpump should be capable of raising at least 10 litres per minute from a depth of 3 metre.
- Reach water within 200mm of the bottom of a tank.
- It should have good durability i.e. capable of lifting a minimum of 100,000 litre before requiring replacement (based on a family of five people with a 20 lpcd for three years).
- Only require basic maintenance - say every 10,000litre before requiring maintenance.
- The footvalve must not leak faster than 0.1 litre per minute.

In addition, it is desirable, but not essential, that handpumps have the following characteristics:

- Be reasonably secure against children pushing stones or pouring liquids into the outlet.
- No part should be easily stolen or removed.
- The outlet must be at such a height that most collection vessels, especially jerricans, can be easily filled.
- It must be ergonomically suitable for a child of about 6 years old to use comfortably.
- Be capable of fitting various types of tank covers, including ferro-cement covers (dome), and through a parapet wall.
- Permit the rising main and footvalve to be withdrawn for maintenance purposes.
- Suitable for production by artisans as an income generating activity.

3. Review of water lifting techniques and selection of candidate pumps

There are four different mechanical principles of transferring water from one location to another and these are shown in Table 1. These can range from simple devices such as scoops to more complex centrifugal pumps.

For the first three methods given in Table 1 these can be further subdivided in to rotary and reciprocating categories, for a taxonomy of pumps see Appendix 2.

Table 1 Summary of four mechanical means of lifting water

Direct lift:	By using a container to physically lift the water
Displacement	Water can be regarded as incompressible and can therefore be displaced
Creating a velocity head	Flow or pressure can be created by propelling water at high speed
Using the buoyancy of a gas	Passing air bubbles through water will raise the level of the surface

(Fraenkel, 1997, p29)

Rather than go in to any detail here an outline of techniques for lifting water in the low head, low flow rate range are summarised below. For a more detailed account, these are well documented by Fraenkel (1997).

To briefly discuss the most common types of low head, low flow capacity lifting devices the following descriptions are given:

3.1. Direct lift

Many of the direct lift methods of lifting water require open access to the water surface, i.e. buckets or containers on ropes or a lever for mechanical advantage supported on a frame. Persian type wheels rotate scoops or buckets in to the water, which transfer the water on the down side of the rotation. These can be employed in small-scale irrigation and to fill cattle troughs. The construction of these is simple and basic requiring a very low skill level.

3.2. Displacement pumps

Lift and suction pumps fall in to the category of displacement pumps. These rely on a piston, which is close fitting within a cylinder containing water. Lift pumps physically lift the water that is above the piston up the pipe to the outlet. Suction pumps have the piston above the surface of the water. By lifting the piston a vacuum is created which displaces the water up the pipe. A one way footvalve is needed to stop the water in the pipe from flowing back in to the well/tank. Figure 2 shows the basic principles of lift, suction and displacement pumps.

3.3. Suction pumps

Suction pumps rely on a piston seal within the cylinder. On the upstroke a pressure difference occurs between the air at the water level and the air in the cylinder chamber. This forces water in to the cylinder, which gradually rises on each successive stroke. The annulus or gap between the piston and the cylinder will affect the performance of the pump. The annulus needs to be at a minimum or even have some interference, and may be lubricated in some cases to reduce friction. Priming may be required to get a pump to work, because water is more viscous than air it helps to improve the seal during the first few strokes. Priming can be achieved by physically pouring water in to the piston chamber or by retaining water in the chamber during non-operation of the pump. The latter requires a footvalve that does not leak or leaks at such a slow rate that the chamber is not emptied before the pump is used again.

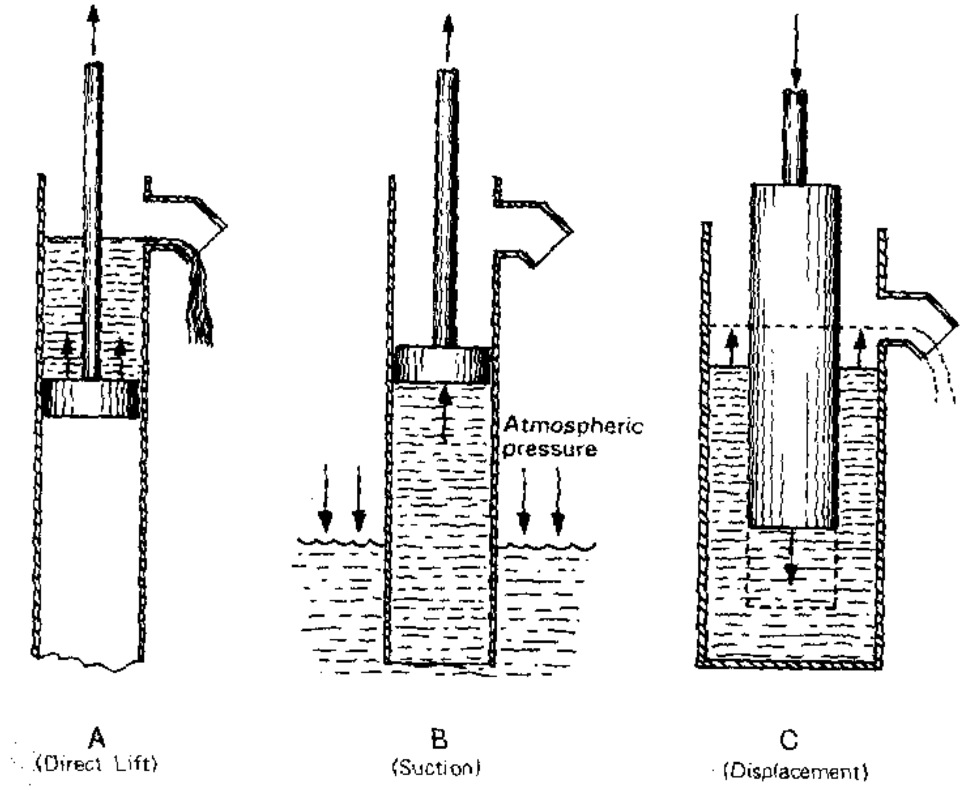

Figure 2 Basic principles of positive displacement pumps

There are limits to how high the suction lift can be. In theory, this is 10.4m at sea level, and in practice, 6.5m is a more practical limit. This will be further reduced by increased temperature of the water and higher elevations. For example, an increase in temperature from 20° to 30° will reduce the suction head by 7%, and for an elevation of 1500m the maximum suction will be around 5m [Fraenkel 1997, p14]. As a general rule for every thousand metres of elevation a loss of 1m suction head will apply.

3.4. Lift pumps

Lift pumps have some similarities with suction pumps in their components but differ in the position of the piston. For lift pumps the piston is below the surface level of the water, and by raising a handle, connected to the piston via a pull rod, water can be drawn up the rising main.

For lift pumps, it is preferable that there is a good fit between the piston and the cylinder but it not as critical as it is with suction pumps.

As Fraenkel relates there is a basic relationship between the discharge rate (Q), the piston diameter (d), the stroke length (s), the number of strokes per minute (n), and the volumetric efficiency (η_{vol}). The volumetric, or hydraulic, efficiency is an indicator of the actual discharge over the swept volume per stroke.

If the swept area of piston is A $= (\pi d^2)/4$

Swept volume per stroke, V $= As$

Discharge rate q $= \eta_{vol} V$

Pumping rate per min Q $= nq$

Then Q $= 60n\eta_{vol}s\pi d^2/4$

The term slippage is sometimes used and refers to the difference between the swept volume and the actual discharge per stroke:

Slippage $X = V - q$

Slippage arises partly because the valves take time to close, they are often still open when the piston starts its upward travel, and because of back leakage past the piston or valve seats. Slippage is therefore normally less than unity, typically 0.1 or 0.2; it tends to be worse with shorter strokes and higher heads (Fraenkel, 1997, p38-39).

In some pumps the volumetric efficiency can be greater than 1. This arises in particular pumps that use the inertia of the water to raise an amount of water. As the column of water is accelerated upwards, it has inertia that keeps the column rising for a short time while the pump is being pushed downwards while the valve remains open. Therefore, the volume of water discharged is greater than the actual swept volume of the piston.

4. Manufacturing environment, competition and materials choice

4.1 Review of handpumps in Mbarara

Figure 3 Semi-rotary handpump

A search of hardware shops in Mbarara, Uganda was carried out to find what types of handpumps were available. The only one found was a semi-rotary type, as shown in Figure 3, and was made in Czechoslovakia. This consisted of a heavy cast iron chamber with a series of internal brass valves. The pump operates through rotating the handle repeatedly through approximately 120°. The pumps are generally very stiff to operate, and pumping is very exhausting work beyond ten minutes. The handpumps cost UGS600,000 (GBP250), no performance data was available with the pumps. This handpump is deemed too expensive and regarded as too difficult to operate, certainly by a child.

4.2 Manufacturing capabilities and materials available in Uganda

A reasonably thorough search of Mbarara, and to a lesser degree other towns, was carried out to find what trade outlets and manufacturing facilities were available which may be drawn on for the purpose of developing handpumps.

Like many Ugandan towns there are a large number of hardware shops dealing in a wide range of hand tools and plumbing fittings of reasonable to good quality products. There were also many steel stockholders and builders merchants in most towns visited. The steel stockholders did not have any stainless steel or brass sections in stock but some were willing to secure an order from Kampala.

Only one engineering workshop capable of any precision engineering was found in Mbarara. This consisted of a centre lathe, drill press, an off-hand grinder and one machinist.

There are many carpentry/joiners located in most towns, and mainly produced beds and cabinets, some of the larger establishment had wood lathes, and were capable of very high quality of craftsmanship. Also, there are plenty of roadside welding facilities available, usually fabricating burglar bars. For a list of common materials, tools and accessories found within a typical market in Uganda see Appendix 3.

4.3 Suitable materials for the rising main and cylinder

A durable, light weight and corrosion resistive material would be ideally suitable as a means of conveying water from the tank. The material must also be capable of being processed with simple and basic tools. This would rule out steel pipes as they are difficult to process without expensive equipment. One material that is widely available, non corrosive and lightweight is PVC.

4.4 The use of PVC as a suitable material for handpumps

There are several valid reasons for using PVC for handpumps, though there are some drawbacks as well. Table 2 gives some advantages and disadvantages of PVC. There is a range of PVC pipes available in E. Africa. These are thin walled low quality with no manufacturing marks for identification.The use of PVC has widely been accepted as a suitable and safe material for use with drinking water As Michael Dudden of the Consumers' Association Research & Testing Centre (CARTL) quotes:

> "The UK Drinking Water Inspectorate, the Swedish Environmental Protection Agency, the Swedish Water and Waste Waterworks Association, the World Health Organisation and the Organisation for Economic Co-operation and Development have confirmed the safety of PVC pipe. All these organisations have approved the use of PVC pipes to carry potable (drinking) water"

Table 2 Advantages and disadvantages of PVC for handpumps

Advantages	Disadvantages
Non-corrosive (esp. in aggressive water conditions)	UV degradation (causes embrittlement)
Light weight	Low impact strength
Low cost	Above ground parts may be subject to high forces: from animals using the pump as a scratching post, pipes being used as a resting post or being accidentally hit with full jerricans and possibility of malicious damage.
Flexibility (i.e. heat manipulation,)	
Ease of transportation (easily carried by bicycle)	
World wide availability	
Secondary uses (recyclable)	
Low cost joining ability (solvent welding)	
Non toxic (through usage) or taste tainting	

5. Calculations of power and efficiency

5.1. Power required from specifications

Determining the power required to operate a handpump is important for both its efficiency and to match the prime mover. The power capabilities of humans at various ages and durations are shown in Table 1 (Fraenkel, 1997, p118). As we are only interested in lifting 20 to 40 litres at a time, the first column is of most relevance.

Table 3 Power capabilities of human beings

Age	**Human power by duration of effort (Watts)**					
Years	5 min.	10 min.	15 min	30 min	60min	180 min
20	220	210	200	180	160	90
35	210	200	180	160	135	75
60	180	160	150	130	110	60

(Fraenkel, 1997, p118)

Table 4 Handpump specifications

Detail	**Symbol**	**Units**	**Value**
Flow rate (discharge)	Q	litre s^{-1}	0.167
Head (maximum)	H	m	4
Inside diameter of riser	d	m	32×10^{-3}
Stroke length	l	m	0.3
cadence	n	Cycles s^{-1}	1.167

To determine the power required for the handpump operating under the specifications in section 2.1, and shown in Table 4 the following calculations show that if:

$P_0 = E.n$

where: P_0 = power (water Watts), E = output energy, n = cadence in strokes per second

and E = mgH

where: m = mass of water lifted per cycle, g = gravity, H = head

$m = v. \rho$

v = swept volume of stroke, r = density of water

Therefore the swept volume of half cycle is:

$v = p.r^2.l \quad = p\ (19.5 \times 10^{-3})^2.\ 0.3 = \mathbf{3.58 \times 10^{-4}\ m^3}$

$E = 3.58 \times 10^{-4}\ m^3 \times 1000kg\ m^3 \times 9.81ms^{-2} \times 4m = \mathbf{14J}$

Therefore: $P = 14J \times 1.167\ s^{-1} = \mathbf{16.38\ Watts}$

If the pump is 40% efficient then the power input P_i = **41Watts**

From Table 3, it can be seen that a 20 year old human is capable of producing 220 Watts effort for a duration of 5mins. From this, we can see that for the power required for lifting water, at the given specifications, a direct lift type handpump would be suitable.

5.2. Losses in the system

It is inevitable that there will be losses for any pump and its prime mover, however for the purpose of this project the pump is the main concern. It takes power to lift the water and to overcome any losses in the system. These losses may be mechanical, hydraulic or combination of the two. The following list shows sources of power losses in a pump:

- Friction in straight pipes (hydraulic)
- Friction from sliding components (mechanical)
- Leakage through pipes and badly sealing valves
- Flow friction through valves
- Headloss at changes in cross-section or flow direction
- Water leaving the handpump has kinetic energy
- Valve operation (delays in opening and closing causes losses)

5.2.1. Pipe friction

To get a reasonable and quick value for frictional losses it can be easier to use charts (as shown in Appendix 4). Using the chart method for a flow rate of 0.3 litre s^{-1} and an internal pipe diameter of 32mm, the headloss equates to about 0.58m per 100m. This is for cast iron pipe and a modifying factor for smooth PVC pipe is given as 0.8, which gives 19mm for a 4m head. Therefore pipe friction at these low flow rates and low head can be regarded as a negligible. But if smaller pipes are used higher frictional head values will be found, for example a 20mm PVC pipe will have 200 mm headloss loss for the same flow rate.

6. Selection of suitable handpumps

From the taxonomy of pumps shown in Appendix 2 it can be seen that there are a number of pumps that are suitable with head ranges far beyond the 4m limit given in the specification at the beginning of this report. The main types that are within the specification are the direct lift reciprocating/cyclic types.

Because of the open access to the water surface for lowered 'container' type lifting devices these incur a high risk of contamination from the container. Moreover there is also a potential for mosquito breeding in any tank without a permanently sealed cover.

For the 'Persian wheel' types the physical size of the tanks makes it unsuitable for abstracting water.

The rotary velocity pumps (propellers, mixed flow, etc) are suitable for the required head but demand a high degree of manufacturing process and precision, which would take the handpump beyond the $10 cost. In addition, the manufacturing capabilities in Uganda or most of E. Africa are not adequate for this at present.

This leaves generally the suction and lift pumps and possibly the rope and washer pumps.

7. Four designs of handpump

From the materials, tools and manufacturing search carried out in Uganda as well as the points made in the above sections a suction pump and three lift pumps were chosen.

The suction pump was based on the Tamana handpump developed in Sri Lanka, which makes use of standard PVC pipe fittings. The three lift pumps chosen were:

- The DTU handpump. A simple bicycle pump modification using a leather washer as the piston (Thomas T, *et al*, 1997).
- The 'Harold' pump which uses a non-contacting simple moulded cup (Whitehead, 2000) and does not rely on any fine precision to produce a lifting action.
- An Enhanced inertia pump which has no piston and relies partially on the inertia of the water in the system.

Details on the manufacture of these four pumps are not included in this report as they are detailed in technical release No TR.-RWH 09 (Whitehead, 2000).

7.1. The DTU Handpump

The DTU Handpump, (an exploded view is shown in Appendix 5) is a simple lift pump and uses a leather stirrup-pump piston, which is available from most cycle shops. The principle of operation is as follows: As the handle is lifted, the water above the leather washer is lifted with it. During this stage, the footvalve is opened and the water fills the rising main below the leather piston. On the downstroke, the footvalve is closed and the water in the lower section bypasses the leather washer to the upper section. Repeating operations transfers water to the outlet. During operation of the handpump, water continues to be discharged from the outlet even on the downstroke: this is because the volume of the push rod displaces water within the rising main.

7.2. The Tamana Handpump

This slightly modified version of the Tamana handpump, (an exploded view is shown in Appendix 6) is a suction pump. The pump relies on a seal between the piston-valve and the bore of the PVC cylinder.

During the upstroke, the piston-valve closes (flat on a PVC support), this creates a negative pressure below the piston, and this draws water into the cylinder through the footvalve. On the downstroke, the piston-valve is opened and water flows through the holes in the support to the cylinder above the piston-valve. On both strokes water is discharged through the outlet, as with the previous handpump the volume of the pull rod displaces water within the cylinder on the downstroke.

Labyrinth seals (a series of seals) can increase the performance of the seal. This version uses only two as a demonstration but more could be added. A suitable length of 1½" PVC pipe is connected to a reducer at the bottom of the cylinder and leads in to the DRWH tank where a floating valve is used for the intake.

7.3. The "Harold" handpump

The Harold handpump is a lift pump (an exploded view is shown in Appendix 7), but differs in the fact that it does not rely on a seal or a flexible membrane within the rising main. The piston, as such, is a moulded plastic cup, which is slightly smaller than the bore of the rising main. This is shaped in such a way that it has greater resistance to leakage on the up stroke and water is lifted by the cup. A small, but acceptable, amount of water will leak past the annulus around the cup. If the cadence is very slow, the leakage past the cup will be large.

The sequence of operation is shown in Figure 4, on the upstroke a), the footvalve opens allowing water into the rising main. On the downstroke b), the footvalve closes, and the water within the rising main flows around and above the cup. Repeated operation c) lifts water to the outlet. Very little water is displaced on the downstroke because of the small volume of the pull rod.

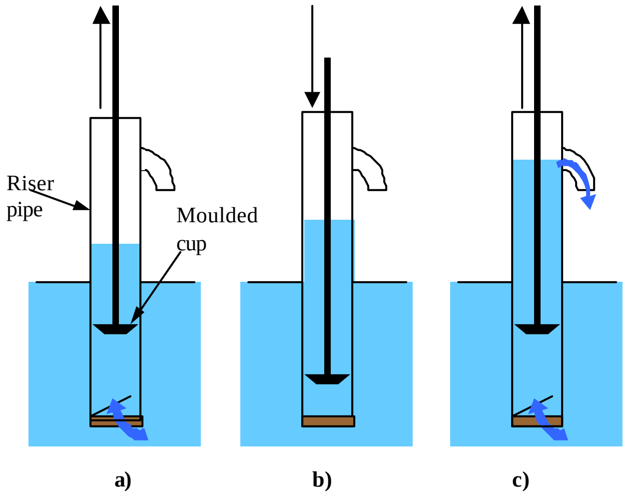

Figure 4 Sequence of operation for the Harold pump

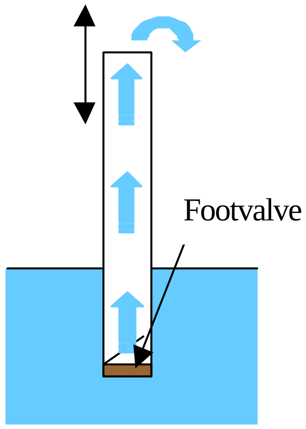

Figure 5 A 'joggle pump

7.4 *The Enhanced inertia handpump*

This pump, (an exploded view is shown in Appendix 8) does not rely on a seal within the rising main, but uses a central tube to lift the water, which overflows in to the rising main.

To explain the principle of operation it is first easier to see how the 'joggle' pump works. If an open top pipe with a footvalve is moved rapidly up and down the inertia of the water will gradually discharge water as shown in Figure 5. One limitation to this is that it will not work at very slow cadences.

By combining this principle with an

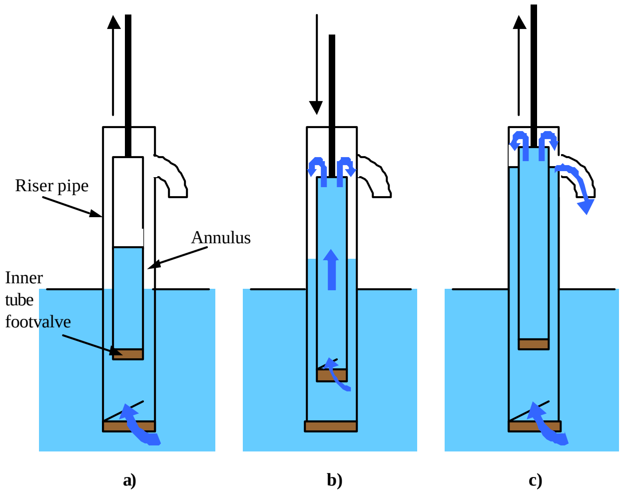

Figure 6 Sequence of operation for the Enhanced inertia pump

outer tube, also with a footvalve, an enhanced principle is observed. A good commercial example of this is the "New Zealand Pump" (www.nzpump.co.nz). A very simplified sequence of operation is shown in Figure 6. During the upstroke a), the inner footvalve is closed and the main footvalve is opened letting water in to the rising main. On the downstroke b), the inner footvalve is opened letting water in to the central tube, meanwhile the main footvalve is closed. Repeated operations c) gradually brings water up the central tube, this then flows through a series of holes in the central tube in to the rising main and is eventually discharged at the outlet.

This handpump seems to operate best when short fast strokes are used. The flow is similar on both strokes of operation, again because of the high displacement from the central tube, which is full of water on the downstroke.

8 Critical components common to all four designs

8.1 Surface roughness and roundness of cylinders

The DTU and the Tamana handpumps rely on a good seal within the rising main cylinder, therefore it is preferable that the surface of the cylinder is as smooth and as round as practically possible.

To determine the smoothness of the bore several samples of uPVC pipe, from different hardware outlets in Uganda, were checked for surface roughness at the Centre for Micro-Engineering and Metrology at the University of Warwick.

At this level the surface roughness is expressed by its Ra value, and uses units in the μm range. Using a pump cylinder with as smooth a bore as possible can reduce the amount of friction (and subsequent wear on the piston) which the user may directly feel as a force to overcome by additional effort. The wear rate will also depend on the hardness of the material used for both the cylinder and the piston seal. A rough pipe surface (a high Ra value) can quickly wear the piston seal and reduce its out flow rate and hence its efficiency.

Table 5 shows the mean surface roughness of two sample cylinders for several popular handpumps available in the early 1980’s.

Table 5 The Ra value of several handpumps with various cylinder materials

Handpump Name	Cylinder material	Ra (mm) Sample 1	Ra (mm) Sample 2
Vergnet	Machined steel	0.57	0.60
Rower	Extruded uPVC	0.55	0.58
Volanta	Glass reinforced plastic	0.57	0.75
Briau Nepta	Extruded brass	0.06	0.21
Bangladesh No 6	Machined cast iron	2.40	2.40
Ethiopia BP50	Extruded uPVC	0.60	1.50
Vew A 18	Chromed brass	0.17	0.18
Bandung	Enamelled steel	0.33	0.60

Compiled from World Bank Technical Paper No 19

In comparison to the Ra values for the manufactured cylinders, Table 6 shows the results of two tests (carried out in the Centre for Micro Engineering, University of Warwick 9/11/00) on five different batches of uPVC obtained in Mbarara, Uganda. Tests 1 and 2 are the values from the same sample on two different areas. Table 6 Ra values from uPVC purchased in Uganda.

Table 6 surface roughness values from Ugandan purchased PVC pipes

Sample No	Ra (mm) Test 1	Ra (mm) Test 2
1	7.00	8.93
2	1.89	2.75
3	1.70	1.80
4	5.38	8.81
5	2.80	2.16

This shows, with the exception of the machined cast iron, the values of the uPVC from Uganda are all higher than those shown in Table 5.

The consequence of having a high surface roughness is that the performance of the handpump will diminish over time rather than preferably remaining reasonably constant. The peaks of the surface will abrade the outside of the piston and decrease its diameter.

9 Selection of two handpumps out of the four designs

To assist in the selection of two candidate pumps, any manufacturing difficulty or specific skill level, as well as the amount time required need to be considered.

9.1 Ease of manufacturing the four handpumps

As mentioned in section 2.1, it must be possible to manufacture and maintain the handpump within East Africa at village level with a set of basic hand tools. Table 7 shows a comparison of the manufacturing time, the number of tools required and the skill level required for manufacturing the handpumps. All the tools used to manufacture the handpumps were sourced from the local market.

Table 7 Manufacturing time and skill level required for the four designs

	DTU	**Tamana**	**Harold**	**Enhanced Inertia**
No of tools required	8	8	10	9
Time to manufacture (hrs)	4	4	3	2
Skill level required	high	Medium	Low	Low
Total number of parts	13	15	13	12
Technicians preferred choice[c]	-	-	1 x 1st choice 8 x 2nd choice	9 x 1st choice 1 x 2nd choice

(Whitehead, 2000)

[c] Based on 10 technicians choice after completing the manufacture of four pumps at a two day workshop at Kyera Farm, Uganda 23rd August 2000.

9.2 Pros and cons of the four designs

To assist in the selection process a review of the four handpumps was carried out, and the responses from technicians who attended the training workshop in Mbarara, Uganda August 2000 were also considered. The benefits and drawbacks of the four designs are given in Table 8.

Table 8 Benefits and drawbacks to the four handpumps

The DTU handpump	**Pros:**	**Cons:**
	• Low No. of tools required • Parts which need replacing are low cost and easy to obtain •	• Time to manufacture is long compared with other the handpumps. • Skill level for manufacture is high • Removal of handpump for repair is time consuming • Fairly high resistance during operation • The leather is susceptible to wear • The output for the input effort was low
The Tamana handpump	**Pros:**	**Cons:**
	• Removal of the pump is easy as it is separate from the tank • High output of water • Skill level required is medium • Very low cost • Very low additional cost per metre • Low no of tools required • Positioning of handpump is ergonomically better for most users	• The rubber pistons wear very quickly • Priming is required if the level of the water is lower than the cylinder • High resistance during operation • Cutting pistons to correct size is time consuming • Manufacturing time is comparatively higher
The "Harold" handpump	**Pros:**	**Cons:**
	• Lower manufacturing time than the previous two handpumps • Very little effort required for operation • Low skill level for manufacture • Expected reliability is good • Lower No of parts	• Highest No. of tools required • Pull rod prone to corrosion • Lower hydraulic efficiency because of gap round the moulded cup • Removal of handpump for repair is time consuming
The Enhanced inertia handpump	**Pros:**	**Cons:**
	• Low manufacturing time • Very little effort required for operation • Low skill level required for manufacture and maintenance • Very good expected reliability • Most favoured to make and use • Small fast stroke length gives a relatively steady flow rate • Acceptable hydraulic efficiency at operators preferred cadence	• Higher cadence required • Most expensive to manufacture • Lower output than other pumps • High additional cost per metre for deeper tanks • Steel screws for the flap valve prone to corrosion (no stainless screws found)

9.3 Costing of the handpumps

A limit of $10 was set as a maximum cost for a handpump as this represents a significant proportion (30%) of the total cost of a plastic tube tank (Rees, 200).

A cost comparison of the four handpump designs was carried out and this showed that all four designs could be manufactured for less than $10 for a 3.5m length pump. It can be seen that there is a significant increase in the cost for each metre added to the length of certain pumps. The individual costs for three lengths and cost per additional meter are given in Table 9 (Whitehead, 2000)

Table 9 Cost comparison for varying length of handpumps

Length	DTU ($)	Tamana[b] ($)	Harold ($)	Enhanced inertia ($)
1.5m	6.50	7.25	4.86	5.52
2.5m	8.14	7.89	6.16	7.68
3.5m	9.78	8.53	7.46	9.84
Additional cost/m of handpump	*1.64*	*0.64*	*1.30*	*2.16*

(Whitehead, 2000)

[b] This includes the footvalve and pipe work in to the tank.

This clearly shows that the Tamana is much lower cost per additional metre than the other handpumps. This arises because the only additional cost is the 1/2" uPVC pipe in to the tank. Compared with the Enhanced Inertia the Tamana is 60% lower in cost per metre.

From the four proposed designs, a selection of two handpumps were chosen on the balanced merits of performance, expected reliability, low precision demand and ease of manufacture as expressed by technicians trained in handpump manufacture in Mbarara, Uganda. The selection process eliminated the DTU and Tamana handpumps for the following reasons.

The DTU handpump gave the lowest discharge rate of the four pumps and the following points show that:

- The force required to operate the handpump was comparatively high.
- The pull rod is prone to buckling, at higher cadences (possibly leading to localised wear).
- Retaining the leather washer on to the pull rod is difficult.
- The leather washer became saturated after a short time and could eventually disintegrate.

- The surface roughness for uPVC pipe was high and would wear the piston.

The Tamana did have the highest discharge rate from the Ugandan performance tests, but summarising the following points, the Tamana showed that:

- The surface finish in the PVC bore was variable.
- The diameters of the pipes are inconsistent.
- The roundness of the pipe could not be guaranteed.
- Rapid wear occurred in the piston valves because of the surface roughness.
- Priming is necessary when the water level is lower than the bottom of the cylinder.
- It was one of the least preferred handpumps to manufacture.

This gave sufficient reason to eliminate the DTU and Tamana handpumps. The Harold and Enhanced inertia handpumps were considered more suitable for a number of reasons, these were:

- Neither of the pumps required any fine precision.
- The manufacturing times were much less.
- A lower skill level was required for manufacturing them
- The reliability was expected to be higher
- They were preferred choice of the technicians.

10 Valve Design and leakage tests

A footvalve is required so that the cylinder retains the water during the downstroke of the piston. There are many styles of valves which operate in different ways, for this project a simple design was required which could be made from easily obtained materials and be made with a set of basic tools. The first design is the DTU valve (Thomas *et al*, 1997), which is made from PVC pipe and a strip of rubber. The second is the Low cost valve (Whitehead, 2000) which is made from a wood and a small rubber disc. Wood was chosen because it is easily obtained, very low cost and is simple to work with. Both valves are shown in Appendix 9.

An ideal valve will have zero 'forward' flow resistance and infinite 'reverse' flow resistance. It will also have an instantaneous response, as the pressure gradient reverses, when opening and closing the valve. Two tests were carried out on the Low cost valves. Firstly, the ratio of the sum of inlet holes area to the pipe area was varied to see if this affected the flow. Secondly, the rate at which the valve leaked was found from a simple test. The DTU valve was only tested to determine the leakage rate. Table 10 shows the dimensional values for the pipes and the inlet holes for three 1mm incrementally larger sizes.

Table 10 Ratio of sum of inlet hole areas to the total inlet area (low cost valve)

Æ 1 1/2" - 40mm pipe	Units	No 1	No 2	No 3
Inside diameter of pipe	mm	34.25	34.25	34.25
Area of inner pipe bore	mm^2	921	921	921
Diameter of inlet hole	mm	6.0	7.0	8.0
Area of inlet hole	mm^2	28.3	38.5	50.25
No of holes in inlet	No	5	5	5
Flow passage ratio =		0.15	0.21	0.27
Æ 1 1/4" – 32mm pipe	**Units**	**No 4**	**No 5**	**No 6**
Inside diameter of pipe	mm	29.75	29.75	29.75
Area of inner pipe bore	mm^2	695	695	695
Diameter of inlet hole	mm	6.0	7.0	8.0
Area of inlet hole	mm^2	28.3	38.3	50.25
No of holes in inlet	No	4	4	4
Flow passage ratio =		0.16	0.22	0.29

The test on the low cost valve was carried out by operating the pump at different cadences and recording the time to fill a 5 litre container. The results of these are shown in Table 11.

Table 11 Results of low cost valve inlet ratio test

Test	Cadence cycles/min	Time to fill 5 litre container (seconds)
Valves: No1 & No4	40	58
Valves: No2 & No5	40	58
Valves: No3 & No6	40	55
Valves: No1 & No4	60	37
Valves: No2 & No5	60	38
Valves: No3 & No6	60	35

This shows that the ratio has almost negligible affect on the flow out of the handpump at these cadences. No detectable change in effort was felt by the operator as the inlet holes were varied.

A larger size hole may eventually collapse if the wall section between the inlet holes is too thin. It was observed that the inlet holes, after approximately 48hours, showed signs of becoming oval. This is arises because of the wood swelling and compressing perpendicular to the grain. A wood that resists water, or is little affected by it, should be used if available (i.e. in the UK Elm would be used). Alternatively, some method of protecting the wood could be done i.e. heating the inlet in food grade oil.

10.1 Valve leakage tests

Ideally, it is preferable that the handpump holds its prime so that next time the handpump is used the first stroke would discharge water. To achieve this the footvalve would have to seal perfectly, in practice, this would be almost impossible to achieve and from the specification we can tolerate a minimum leakage of 0.1 litre per min.

To determine the amount of leakage a series of short tests were carried out which involved filling the rising main with water and measuring the amount of water at timed intervals as it leaked past the valve. The valve end was placed above a container with graduated markings of 20 ml. At 15 second intervals the volume of water in the container was recorded. This test was carried out on both the DTU valve and the Low-cost valve. The graphical results of these tests are shown in Appendix 10, and these illustrate the different characteristics of both valves.

The graph of the DTU valve shows that the leakage rate actually rises (almost to a square law) with pressure across it. This suggests a roughly consistent leakage aperture. It was expected that the water pressure acting on the inner tube section over the perforated pipe would be greater at higher heads. Then at lower heads, the pressure would be less and the rate of leakage would increase but this was not the case.

The Low cost valve showed a more complex three-point characteristic. Initially at the higher head, leakage is high but falls as the pressure falls. Following this is a zone of almost constant leakage rate that is independent of pressure over a 0.5m range. Finally, the leakage rate rises over the last metre as the pressure falls. A fast leakage rate at the start may be because of some settling of the valve and/or some ‘puckering’ of the valve instead of laying flat over the inlet holes.

All this suggests that the leakage aperture varies with pressure. It was expected that the leakage rate would gradually increase as the pressure is reduced on the valve, and leaking faster as the head remaining tended to zero. The total time for the column to fully discharge was 6.5 minutes, showing that the low cost valve has a mean leakage rate twice that of the DTU valve. In both tests, the leakage rate varies with the pressure drop across the valve. The two mechanisms at work here are: a) higher pressure forces the water faster through the apertures in the valve body, b) the aperture size is reduced by the pressure forcing the valve flap harder onto the inlet holes in the valve body.

The low cost valve was chosen as the most suitable design mainly because the force required to operate the pump was significantly less than that for the DTU valve. The DTU valve performance depended on getting the right sized inner tube to the inlet pipe, older and less elastic tubes worked more efficiently. Whereas the response and efficiency of the low cost valve was much more desirable despite the lower leakage rate.

11 Performance tests

A series of performance tests were carried both in Uganda and within the laboratory at the University of Warwick. In Uganda, this consisted of some basic preliminary tests on four demonstration models to compare the handpumps performance. A spring balance was attached to the handpump handle to show the force required during the upstroke. A container was placed at the outlet, of known volume, and filled and the time subsequently recorded. The results given in Table 12, show that force required to lift water was 7 and 8 fold less for the Harold and Enhanced inertia handpumps over the DTU and Tamana handpumps respectively. The Harold and Enhanced inertia handpumps also showed lower flow rate output than the Tamana handpump, but higher flow rate than the DTU handpump.

11.1 Ugandan-based performance tests

Table 12 Performance comparison of the four handpumps

Variable	DTU	Tamana	Harold	Enhanced inertia
Internal diameter of rising main (mm)	39	39	39	39
Length of rising main (mm)	530	530	530	530
Stroke length (mm)	330	254	406	102
Kg force to lift water	8	7	1	1
No of cycles/jerrican	134	114	159	142
Output Litres/min	7.55	11.6	8.93	8.43
Minutes to fill 20 litre jerrican	2.65	1.91	2.24	2.37
Apparent vol. efficiency	0.38	0.58	0.26	1.16
Reliability[a]	low	low	Medium/high	High

(Whitehead, 2000)

[a] This is based on the limited field trials carried out in Uganda, and is the expected reliability: low = 2 months, medium = up to 6 months and high = 12 months.

The Table 12 shows that the volumetric efficiency of the DTU and Harold pumps are quite low. The volumetric efficiency of the Enhanced inertia is greater than unity. Though inertia type pumps, as mentioned earlier in section 3.4, can give a value greater than one it seems unlikely when there is a short column of water. There seems little else to explain this high value and a repeat of the test under the same conditions needs to be carried out to confirm this high value.

11.2 University based performance tests

The performance tests carried out at the University were achieved using the set up shown in Figure 7. During the tests the head, cadence and stroke length were varied over a suitable range. The time to fill a 5 litre container and the operators heart rates were recorded. Any comments by the operator were also noted. The results of the performance tests carried out in The University of Warwick are shown in Appendix 11

The performance tests had two main functions. Firstly, that both handpumps could be compared to each other show any differences in their performance. Secondly, to see what changes the variables have on the operator with respect to input effort. Three males and one female were used with ages ranging from 20 to late 30's.

The cadences used were 50, 60 and 70 cycles per minute, 40 cycles was used in the first tests but was regarded as too slow and consequently dropped from the remaining tests. The cadence that most operators preferred was 60 cycles/minute.

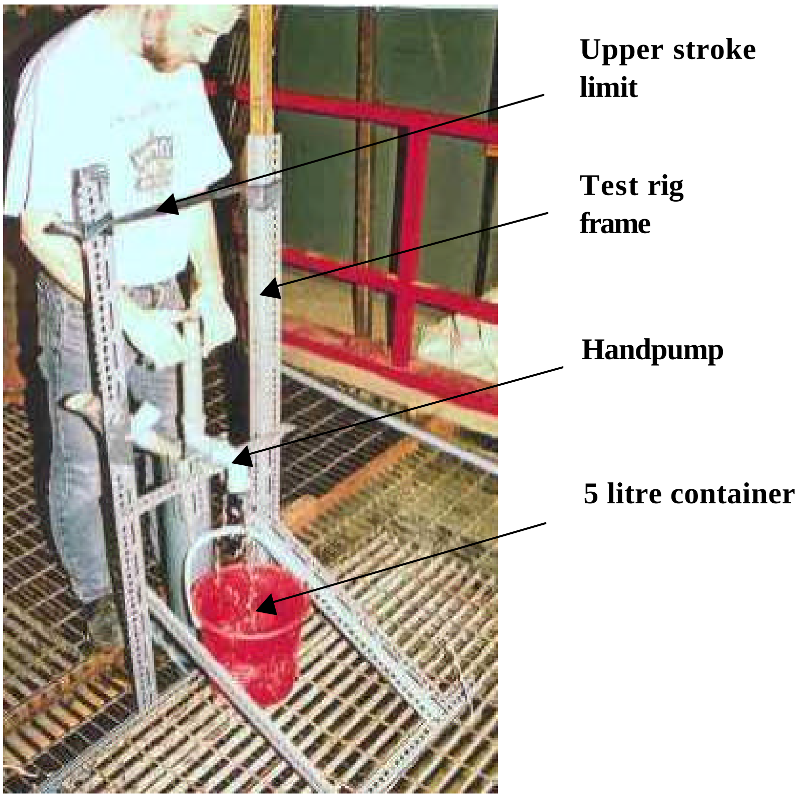

Figure 7 Performance test set up

It was expected that the flow rate and the volumetric (or hydraulic) efficiency would increase with higher cadence and longer stroke lengths, which it did. Though there is a limit to this, as it becomes increasingly difficult to operate at higher cadences with long stroke lengths. In addition, the returns on volumetric efficiency, for a higher cadence, are not worth the additional effort as will be seen later in section 12.

11.3 Heart rate monitoring

During the performance test each operator’s heart rate was monitored with the aid of a standard electronic monitor worn around the chest as used by athletes. As the cadence and head was increased it was reasonable to expect an increase in the heart rate as well. This would give an indication of the amount of additional effort the operator had put in as the head and cadence were increased.

From the results in Appendix 11, it can be seen that there are some cases where the results are conflicting. For three of the operators, their maximum heart rates had increased by very much the same (avg. 12%). These had mainly occurred towards the highest heads and highest cadences. But one operator showed their highest heart rate increased on two occasions, firstly at the lowest head and highest cadence and secondly at a much lower cadence and a mid-range head.

The female operator showed a much larger increase in heart rate (33%), this had occurred at a higher cadence but also at a mid-range head.

In general, it has shown, given a small number of tests, that the increase in heart rate is small and did not show any of the operators to be expending much of there potential.

11.4 Moulded cup size tests for Harold handpump

To see how varying the diameter of the moulded cup affects the performance a short series of tests were carried out. This involved timing how long it took to fill a 5litre container at a cadence of 60 cycles and a 0.25m stroke length for five different diameter moulded cups. This showed that, as was expected, the volumetric efficiency increased as the cup size increased. It also showed that the effort required in pushing the handle down increased on the upstroke as the cup size increased. It may seem more desirable to either have the same or similar effort to operate the handpump on both the up and down strokes. To rectify this a series of holes were drilled around the cup and a valve incorporated. This had the desired effect but meant more work on the component was required. The results of the tests are shown in Table 10.

Table 10 Results of moulded cup tests for 0.25m stroke length

Cadence (cycles / min)	Bore diameter of pipe (m)	Diameter of moulded cup (m)	Time to fill 5 litre (s)	Flow rate (litre / min)	Upstroke effort (1 to 10)	Downstroke effort (1 to 10)	Volumetric efficiency
50	0.036	0.032	Too slow	-	0	1	-
60	0.036	0.033	240	1.25	1	2	0.08
60	0.036	0.034	70	4.29	2	3	0.28
60	0.036	0.035	30	8.57	2	6	0.56
60	0.036	0.036	25	12.00	6	9	0.79

11.5 Modification to designs

A modification to the design of the Enhanced inertia pump was required because UK-made pipe differed in size to that purchased in Uganda. This difference resulted in a reduced annulus and an unacceptable performance.

Figure 8 shows a cross-section of the Enhanced inertia pump clearly showing the annulus between the two pipes. The area of the annulus can be expressed as a ratio of its area to the outer pipes bore area. The annulus ratio for UK-made pumps was 0.14, and a higher value (0.17) was found for those made in Uganda. Even at slow to moderate cadences some of the water within the riser was unable to discharge through the outlet and vented through the annulus at the top of the rising main instead, as shown in Figure 9 a). This was solved by removing a 0.4m section of the upper central pipe and replacing it with a steel pull rod as shown in b). This was fixed to the

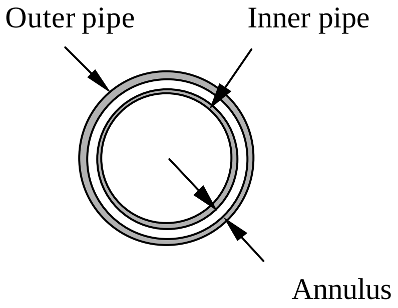

Figure 8 Cross-section of inner and outer pipes

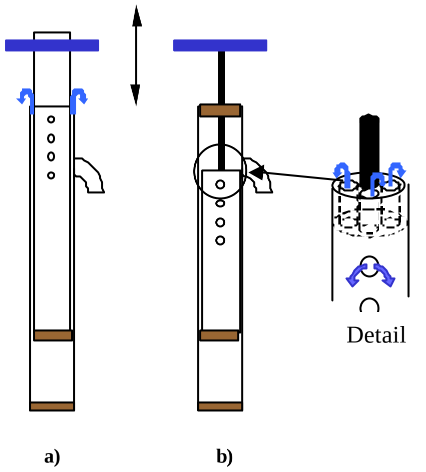

Figure 9 Modification of the pump and water flow path

inner pipe with a wood inlet as used in the footvalve. The details in Figure 9 b) shows the flow path through the wood inlet after the modification.

For a constant flow rate (Q) reducing the annulus area (A) increases the water velocity (v) (from mass continuity: Q = vA). Given the increased velocity caused by the reduced annulus area a significant fraction of the water continues the short distance to the top of the riser pipe and leaks out. By increasing the annulus, the velocity of the water is reduced such that all the water flows through the outlet.

One drawback to this modification is that using a steel pull rod will lead to corrosion and reduce the quality of the water. Stainless steel is not readily available in Uganda. Galvanising the pull rod may be an option as this process is used on corrugated roofing sheets in Uganda and would greatly reduce the level of corrosion.

12 Durability testing of the handpumps

It is important that the handpump performs satisfactorily over a period of time before the pump is either beyond repair or no longer lifts sufficient water for the household. A reasonable expected life for the pump had been decided in the specification as three years. If a family of five people use the handpump to abstract 20 lpcd over three years then this amounts to 109500 litre over the expected life of the pump. From the performance tests 15 litres / minute could be taken as a reasonable discharge rate, and this would equate to 122 hours or 5 days continuous use. To replicate this a durability test rig was designed and built at the University of Warwick to give a reciprocating motion powered by an electric motor and geared down through two variable speed gearboxes. The output speed could be varied between 17 and 400 cycles / min.

The output shaft of the final gearbox was attached to an arm 0.15m from centre of rotation, giving a stroke length of 0.3m. The head was set at of 2.65m. The reciprocating arm was linked to the motor arm and the pull rod with rod end bearings, This would allow for any slight misalignment in the motors rotational plane and the handpump's translational plane.

Because of the physical size of the test rig it was necessary to build it over an existing 2.5m deep pit in the Engineering workshop at the University. A sketch of the endurance test rig is shown in Figure 10 indicating the main components. The water discharged from the handpump was re-circulated back in to a large reservoir in the bottom if the pit, via a flow detection chamber. Because the discharged flow from the outlet is in a non-steady state and difficult to measure, the flow was diverted from the outlet in to a 15 litre container and the number of cycles to fill this was recorded with a tally counter. This was repeated during the test to show any changes in the outlet flow over the life of the handpump.

As the handpump was to run continuously over 5 days, there was a possibility that the motor would still run even if no flow occurred. Therefore, the flow detection chamber housed a horizontal float switch, and operated a relay to cut the power supply if the flow stopped.

A digital clock was fitted which showed the lapsed hours and minutes whilst flow occurred. As the flow rate per cycle is known a reasonably accurate number of litres pumped could be found.

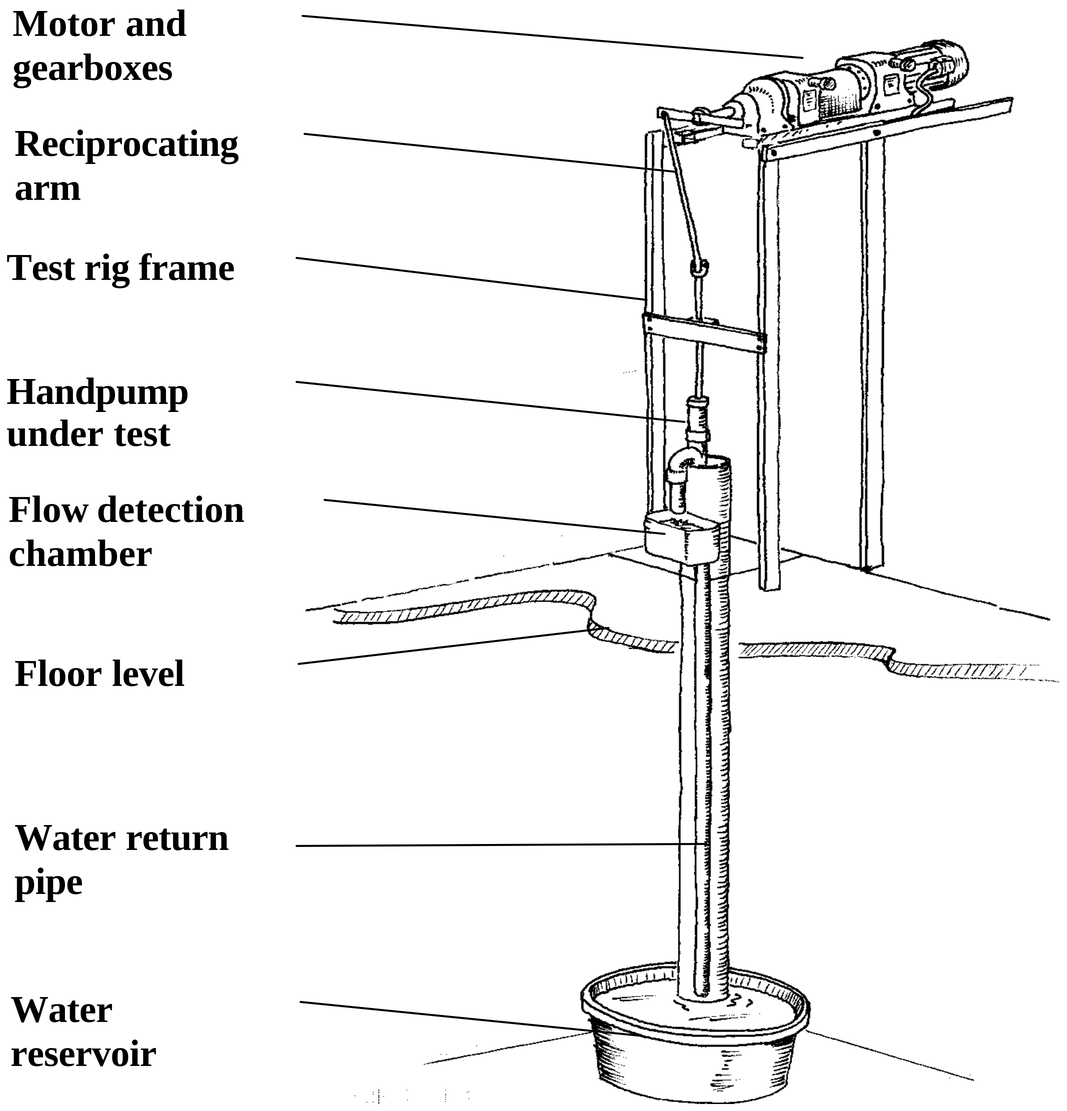

Figure 10 Endurance test set-up

The objectives of the durability test were to indicate the following points:

- The failure mode of the handpump
- Reduction rate of out flow over time
- Where any localised wear occurs and how much it may have worn by
- Time between failures
- Durability comparisons between each handpump

The Harold handpump was tested first and a number of dimensional checks were carried out before the test commenced. Firstly the moulded cup for the Harold handpump was measured across its diameter in three places (120°). This is because accurate roundness of the cup during manufacture can not guaranteed. The dimensions of the moulded cup are shown in Figure 11.

The hole size of the pull rod support bush was also checked, as this was regarded as high wear area. The diameter of the hole at the start of the test was ∅8.8mm.

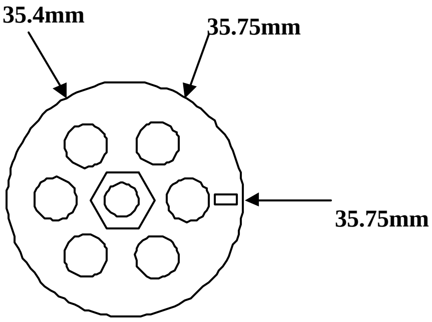

Figure 11 Dimensions of the molded cup at start of the endurance test

The reason for failure most expected from the Harold handpump were that firstly, the wear in the moulded cup would reduce its performance until the flow fell below 10 litre per minute before the end of the endurance test. Secondly, one of the valves may fail (tears or splits) during its half-million plus cycles.

A two hours 'bedding-in' period was carried out prior to the tests so that any stiffness in the system may be reduced or that any problems with the set up could be detected and rectified. The results of the durability tests for the Harold and Enhanced inertia handpumps are shown in Table 12 and 13 respectively.

Table 12 Harold handpump durability results

Cumulative water lifted (litre)	Normalised Flow rate	Volumetric efficiency	Failure mode	Wear in piston Æ (mm)	Wear in rising main Æ (mm)	Diameter of hole in pull rod bush Æ (mm)
0	1.00	0.71	-	0	0	8.8
56,767	0.87	0.64	-	0	0	-
63,302	0.91	0.66	-	0	0	-
74,474	0.89	0.65	-	0	0	-
95,974	0.87	0.64	-	0	0	-
113,081	0.94	0.69	-	0	0	-
120,245	0.94	0.69	-	0	0	9.5

12.1 Observations of the Harold handpump

After completing 143 hours, and 590,000 cycles, of continuous running, the handpump was dismantled and the following points were observed:

- The inlet valve showed signs of indentation from the water pressure acting on the area of each of the five inlet holes (see Figure 12a)
- Moulded cup showed no visible sign of wear
- Stress marks evident on the edge of some of the holes in the moulded cup (see Figure 12b) N.B. these are not at the thinner sections between the holes but at the top of each hole.
- Moulded cup valve starting to show signs of being cut from the moulded cup holes (see Figure 12c)
- Bottom section of the handpump rising main was removed and no significant wear was detected, only small surface scratches on one side if the pipe.
- On removing the handpump, the volume of water remained in the rising main with a very low leakage rate. This was suspected to be fine debris settling and compacting under the valve and actually giving a better seal!

Figure 12 a) b) c)

It can be seen from the results in Table 12 that the volumetric efficiency had dropped by 7% during the first 57,000 litres, with a relatively level efficiency for the next 40,000 litres. After this, there is a rise to within 2% of the original efficiency. One explanation that could be given for this is that some particle may have become lodged under the moulded cup valve, of sufficient size to cause some back leakage. This then may have been dislodged before the last 25,000 litres. This would explain a lower volumetric efficiency and account for the reduction and final increase in the flow rate as shown in the normalised flow rate in Table 12.

12.2 Observations of the Enhanced Inertia handpump

Table 13 shows the results of the endurance test, which ran for 167 hours. During this period no mode of failure or decline in flow rate or efficiency was found.

Table 13 Enhanced Inertia handpump durability results

Cumulative water lifted (litre)	Normalised Flow rate	Volumetric efficiency	Failure mode	Wear in inner pipe Æ (mm)	Wear in rising main Æ (mm)	Diameter of hole in pull rod bush Æ (mm)
0	1.000	0.77	-	0	0	9.5
22,012	0.997	0.77	-	0	0	-
48,020	0.997	0.77	-	0	0	-
74,106	0.997	0.77	-	0	0	-
95,270	0.997	0.77	-	0	0	-
164,422	0.997	0.77	-	0	0	12.5

Inspection of the internal parts of the handpump, after the endurance test, showed little sign of wear either on the inner pipe or on the bore of the outer pipe. Both valves showed signs of deformation (similar to the Harold handpump) where the rubber had repeatedly been depressed into the wood inlet holes.

The only other indication was some localised surface scratches on the outer pipe bore where the inner pipe had contacted it during its 700,000 cycles. The only external part that had worn was the wood support bush for the pull rod, and this had become oval but of no detriment to the handpump's performance.

Figure 13 shows the standardised flow rate against cumulative litre for both the Harold and Enhanced inertia pumps.

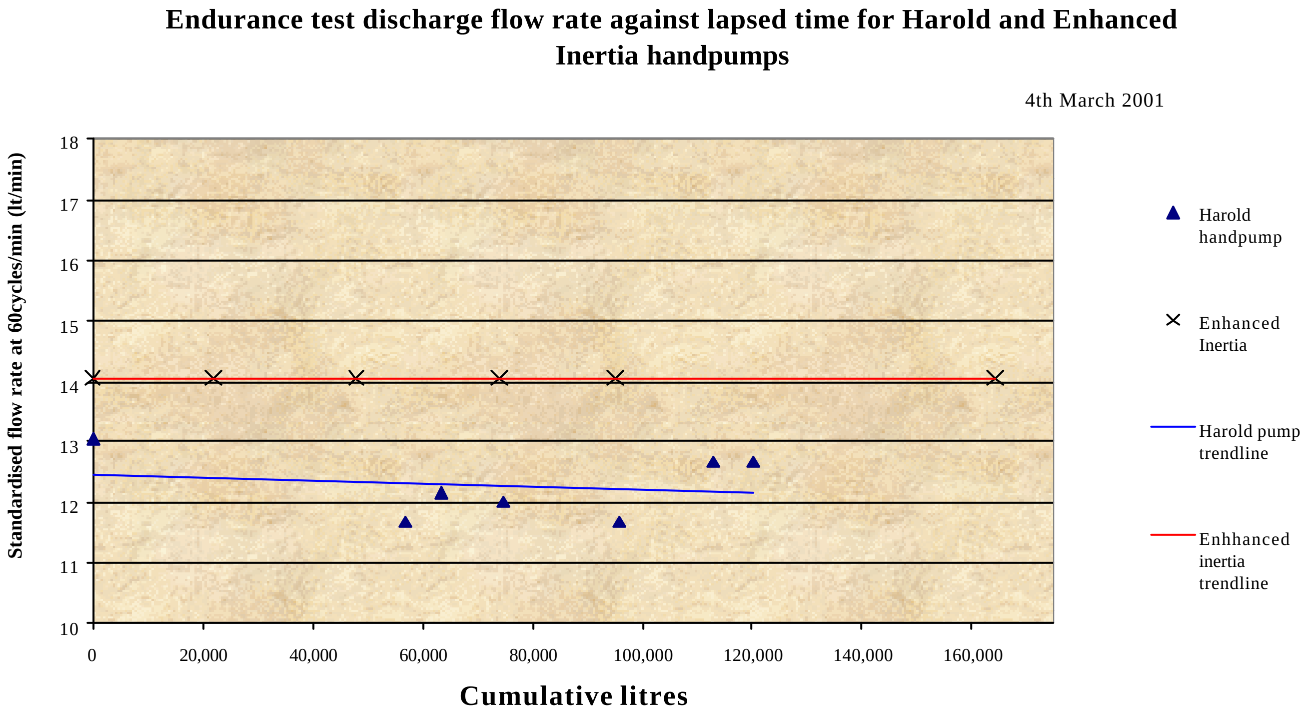

Figure 13 Comparison of the Harold and Enhanced inertia endurance tests

It was hoped that some failure or drop off in efficiency had occurred so that the handpump could be analysed and possibly improved. To try to cause a mode of failure the cadence was increased by 1.5 and run for a few hours. This resulted in a sudden failure rather than it being gradual as the riser pipe was forced off the outlet tee. The joint was thoroughly cleaned and re-cemented, and ran at the same cadence without any other failure for several hours.

Figure 14 shows a graph of volumetric efficiency vs. cadence for two stroke lengths, the dotted lines are the upper and lower limits for comfortable operation. This was done to see how a doubling of cadence and a halving of stroke length (which gives the same volume per unit of time) affects the efficiency. This shows for example at a cadence of 35 cycles per minute and 0.3 stroke length the efficiency is 62%, and if the speed is doubled and stroke length halved the efficiency is 60%, showing very little difference. Through the comfortable operating range, the longer stroke length is more efficient for a given cadence.

If the cadence were increased much beyond 70 cycles per minute an operator would find it difficult to maintain a 0.3m stroke length. The graph in Figure 15 shows the product of the two stroke lengths and cadence against efficiency. This shows that for lower cadences there is very little improvement in efficiency for given different stroke lengths. Though there is a tendency for the longer stroke length to show some slight improvement in efficiency at higher cadences.

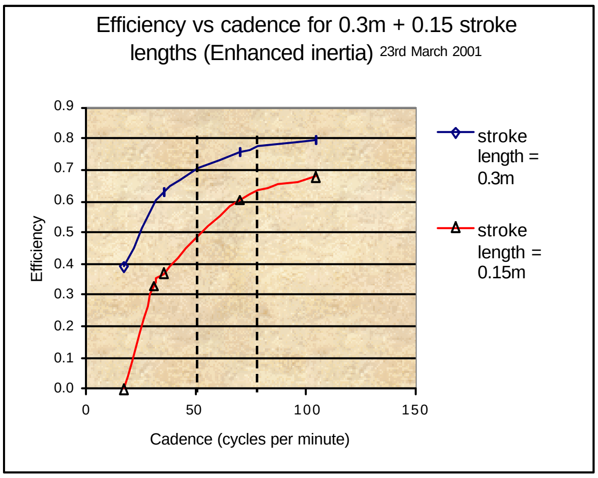

Figure 14 Graph of efficiency and cadence for two stroke lengths

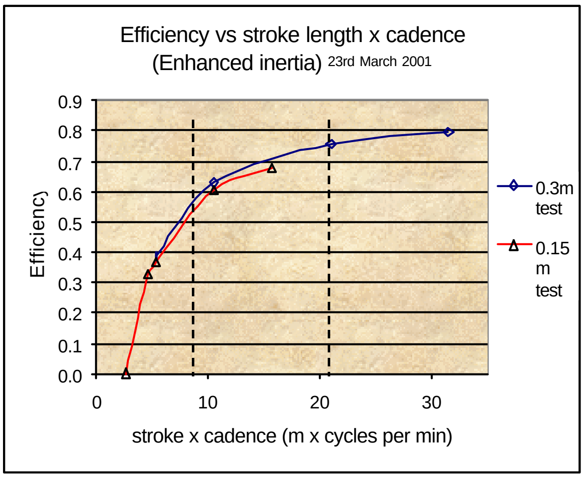

Figure 15 Graph for the product of stroke length and cadence vs. efficiency

In summary of the Enhanced inertia handpump endurance test: because there was no failure mode or a gradual decline in the flow or volumetric efficiency, very little can be said other than the handpump has been shown to be a very durable and reliable handpump. Also, that the handpump would need little maintenance and was more than capable of lasting three years under normal operating conditions.

Last minute update: after completing the Enhanced inertia endurance tests, the pump was further tested at a cadence of 70 cycles per minute and a 0.3m stroke length and was left to run until it stopped. The result of this was that it was still running after 267 hours, and had lifted 261,000 litres of water.

12.3 Safety aspects of the endurance tests

Because of the risk of injury to persons from the reciprocating motion and prolonged test period (two-weeks continuous running), a significant amount of thinking and work was done to assess and remove potential dangers as far as is practically possible. This involved some liaison with the Health and Safety Officer at the University and with the Chief Technician in the engineering workshop.

After consultation with the above, the main points considered and relative actions were as follows:

- Prior to building the test rig a PAT test was carried out by an electrical technician to ensure the electric motor was safe to use.
- Mesh guarding was put around all moving parts
- Bunting was put around the test rig area
- Electrical lights and conduits in the pit were checked as suitable for outdoor weather use
- Continuous running notice was attached to test rig (and relevant people informed: security)
- Power supply had:
  a) over current protection, b) no-volt drop out, c) earth leakage protection.
- A float switch was incorporated to detect handpump delivery flow: power cut out if no flow detected.
- Railings surrounded the pit, and bunting was put up within the pit on open floor level areas.
- Water flow was highly unlikely to reach 415v supply during testing

Table 14 shows possible modes of test rig failure and of the procedure or protection that was used to reduce the danger.

Table 14 Test rig failure and protection procedure

Area of failure	Protection/procedure
· Linkage/reciprocating arm/rod end breakage	· Flow from pump would stop and float switch will cut power to motor
· Frame and/or motor mounting bolts become loose	· Periodic checks to ensure tightness

13 Feedback from Uganda on training and handpumps installed on tanks

13.1 Training

Following a seminar on DRWH tanks built at Kyera Farm, which was attended by several members of NGO's from around E. Africa, a training workshop for handpump manufacture was held for ten representatives on August 22 - 23rd 2000. This involved each participant building four short demonstration handpumps. A handpump manufacturing manual and certificate was presented to each participant on completion.

Correspondence from Moses Byaruhanga, (a co-ordinator for URDT, Kampala) 17 weeks after the training course, stated that "so far from the knowledge we got from Kyera farm, we have trained another 20 new local masons in pump fabrication and repair"

A similar one-day workshop was held for the ten masons and labourers who built the tanks at Kyera Farm. One mason, who had attended the one-day workshop, was building a 25m^3 tank in Mbarara and had decided to make and install an Enhanced inertia handpump himself during September 2000 (no feedback on this at present).

13.2 Handpumps installed in Uganda

A Harold and an Enhanced Inertia handpump were installed on two plastic tube tanks (see Figure 13) built on Kyera Farm, Mbarara in August 2000. Both these handpumps were installed and made by the first group of trainees at the training workshop.

From returned survey forms for August to November on tank use the remarks for the Harold handpump were:

August: Rust was evident in the abstracted water
September: Not functioning
October: Not functioning
November: Functioning

The reason for not functioning for two months or how the handpump was repaired was not recorded. The Enhanced Inertia handpump functioned for four months without any problems.

A separate and more detailed survey from (see Appendix 12) was sent with specific questions relating to the Harold and Enhanced inertia handpumps performance. This was sent to Kyera farm in Mbarara, Uganda in December 2000, a summary of eight questionnaires returned showed that:

- The two Harold handpumps installed in August 2000 were used to fill one jerrican everyday for each household.
- The time to fill a 20 litre jerrican was between 5 and 6 minutes.
- One breakdown had occurred on one handpump in five months since installation: this lasted two weeks, this occurred because of the moulded cup becoming detached from the pull rod. This was repaired by one of the trainees who attended the workshop mentioned in section 13.
- Rusting was still a problem.
- Children found the pump difficult to use.

This clearly indicates, as shown in Figure 13 that the handpump is too high, at the bottom of the stroke the handle is above waist height. This would make any reasonable upstroke length difficult for the child.

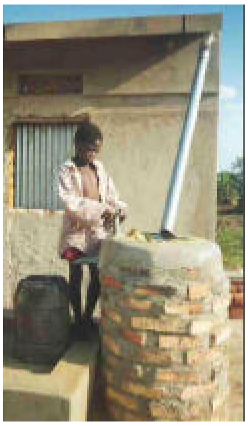

Figure 13 Pump height problem for a young boy

The time to fill the jerricans was far too slow, and was equivalent of 3.5 to 4 litre per minute. This either suggests that the operator was using too low a cadence, an estimated time rather than an accurately timed one has been recorded or the poor performance indicates some malfunction of the valve or moulded cup. Also, the handpumps are not being used for abstracting anywhere near 100 litre per day. This would mean an extended life for the pump well beyond three years.

For the four Enhanced inertia handpumps that were installed the following main points were noted:

- Almost all the pumps were used to fill on average two jerricans each day.
- The average time to fill a jerrican was 4 minutes.
- No breakdowns had occurred, although on one occasion children had put stones through the outlet, but the pump was soon repaired.
- Children find the handpump difficult to use because of its height.

Again, the height of the pump is not suited to children, as the height set from the jerrican stand to the handle was 0.775m. It may have been better to measure the height of all users hands at their lowest position and found a compromise in favour of the most frequent users height before the handpumps were installed.

14 Final recommendations

There seems little doubt from the test results of all the performance and endurance tests that the Enhanced inertia pump has proved to be the most durable and reliable handpump of the two. This is backed up by the feedback from Uganda on the pumps installed in August last year showing the Harold handpump was much less reliable, and the Enhanced inertia pump was still working satisfactorily. On the strength of these points, the Enhanced inertia pump is recommended as the final choice of handpump to install.

The Harold pump could be recommended in circumstances where the cost to the user is of concern. From section 9.3 it was shown that for a 3.5m length pump, the Harold pump cost $2.4 less than the Enhanced inertia pump. However, if the pump is more prone to reliability problems, then the long-term cost of the Harold pump could be greater.

A set of technical drawings for the Enhanced inertia handpump is included at the back of this report.

15 Means of propagation

The purpose of propagation is to reach and disseminate such information specific to this work to those that may benefit from it. The benefit may be from actual use (an improvement in water quality, or a reduction in time spent walking to some other source) or that the handpumps could generate income and improve the wealth of the individual/family. Some means of propagation have already been mentioned in earlier sections but are reiterated in the following list:

- A one-day training workshop was held for 10 fundies (craftsmen) at Kyera farm, Mbarara, for handpump manufacture.
- A two-day training workshop for handpump manufacture was held for 10 NGO representatives in July 2000 at Kyera farm, Mbarara. Mostly
- The Technical release: '*TR-RWH 09 - Low cost handpumps for water extraction from below ground water tanks - Instructions for manufacture'*, has been on the DTU's web site since September 2000 accessible at: http://www.eng.warwick.ac.uk/DTU/workingpapers/tr/tr09/tr09.html
- The handpumps were signposted in 'Footsteps, No.46 March 2001' Appropriate Technologies, by Tear Fund, a quarterly newsletter for development workers around the world.

16 Further work

The Enhanced inertia handpump has shown that it is capable of pumping water on condition that some annulus size is met. The precise way this handpump operates has proved to be very difficult to analyse and remains to be explained. It was found that the pump's performance is sensitive to the size of the annulus and some optimum size or annulus area ratio needs to be satisfied. As pipe sizes can and do vary over different batches, checking the size is important. Further work is recommended to determine the pumping principle and from this find the optimum size of pipes to give the best flow rates. Some method of controlling the diameter, at the top section of the inner pipe, may prove better than replacing it with a steel rod as explained in section 11.5. This may be achieved by heating the top section and a pushing it through an orifice machined to the required size.

17 Conclusions

This project has proved successful in a number of ways and the majority of the criteria have been fulfilled. It is regarded successful inasmuch as the project was completed on time and one of the handpumps, which was thoroughly tested for endurance, can be recommended for a DRWH system. This has demonstrated that a handpump can be manufactured with very low precision at low cost and be capable of lifting water above 10 litre per minute.

The Enhanced inertia handpump has proved to be a very reliable and durable method of abstracting water for low heads and low flow rates. The performance tests showed that the pump exceeded the specified minimum by 50%, and at a cadence of 70 cycles per minute, 15 litres per minute could be discharged with little exertion by the user.

The specification gave a life of the handpump as 3 years, this may have been underestimated as the endurance test showed it capable of working the equivalent of at least 7 years (and lifting 255,000 litre). A 5 year working life may have been a better specification in retrospect.

One of the main criteria was the cost of the pump, though this was kept just under $10 (including labour cost) for a 3.5m length pump it is doubtful the cost could be reduced further unless material prices came down.

Feedback from handpumps installed in Uganda showed that the hydraulic efficiency is suspected to be low gauging from the time required filling a 20 litre jerrican. From the results of this project, some indication of optimising the efficiency, (higher speed and short stroke versus lower speed and longer stroke), needs to be disseminated with the handpumps. However, an operator's preference in cadence and a stroke length may probably over ride a higher efficiency.

The final two designs were regarded as suitable for production by artisans This was demonstrated by the technicians participating at the training workshop in Mbarara, Uganda who built the Enhanced inertia pumps in two hours! Though whether this would be an income generating activity remains to be seen.

The endurance test was run continuously over a number of days and can therefore be regarded as dissimilar to the actual operation of the handpump. On this basis, the handpump may fail for other reasons such as UV degradation, corrosion of any of the small steel screws in the valve or the wood inlet perishing. Some form of protection would be required to prolong the life of the pump.

The two main failings were firstly, that the low cost valve did leak faster than specified, but this is a minor problem as it takes very few strokes before water is discharged even at higher heads. Secondly, if a steel pull rod is used in the modification of the Enhanced inertia pump, corrosion will affect the quality of the water which would be unacceptable for potable water. However, this may be overcome by galvanising if the cost would permit it.

The enthusiasm of all the technicians and others who have come across the pumps via the web site have shown that there is a need for these pumps. By installing an appropriate DRWH system and incorporating an Enhanced Inertia handpump, a large number of people's lives could be improved.

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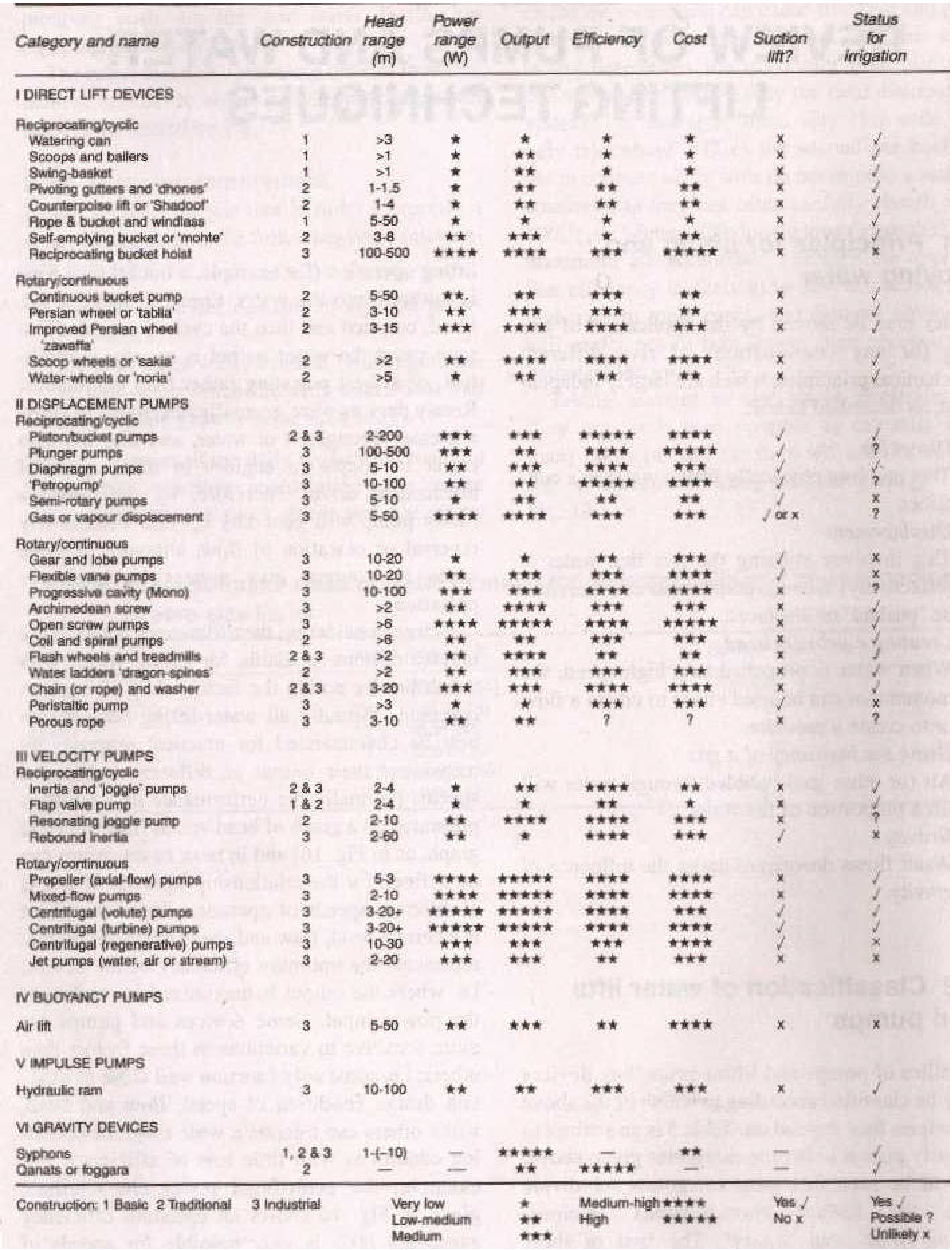
Appendix 1 Project Plan

Appendix 2 Taxonomy of pumps and water lifts



Category and name	Construction	Head range (m)	Power range (W)	Output	Efficiency	Cost	Suction lift?	Status for irrigation
I DIRECT LIFT DEVICES								
Reciprocating/cyclic								
Watering can	1	>3	★	★	★	★	x	✓
Scoops and bailers	1	>1	★	★★	★	★	x	✓
Swing-basket	1	>1	★	★★	★	★	x	✓
Pivoting gutters and 'dhones'	2	1-1.5	★	★★	★★	★★	x	✓
Counterpoise lift or 'Shadoof'	2	1-4	★	★★	★★	★★	x	✓
Rope & bucket and windlass	1	5-50	★	★	★	★	x	✓
Self-emptying bucket or 'mohte'	2	3-8	★★	★★★	★	★★	x	✓
Reciprocating bucket hoist	3	100-500	★★★★	★★★★	★★★	★★★★★	x	x
Rotary/continuous								
Continuous bucket pump	2	5-50	★★	★★	★★★	★★	x	✓
Persian wheel or 'tablia'	2	3-10	★★	★★★	★★★	★★	x	✓
Improved Persian wheel 'zawaffa'	2	3-15	★★★	★★★★	★★★★	★★★	x	✓
Scoop wheels or 'sakia'	2	>2	★★	★★★★	★★★★	★★★★	x	✓
Water-wheels or 'noria'	2	>5	★	★★	★★	★★	x	✓
II DISPLACEMENT PUMPS								
Reciprocating/cyclic								
Piston/bucket pumps	2 & 3	2-200	★★★	★★★	★★★★★	★★★★	✓	✓
Plunger pumps	3	100-500	★★★	★★	★★★★	★★★★★	✓	?
Diaphragm pumps	3	5-10	★★	★★★	★★★★	★★★	✓	✓
'Petropump'	3	10-100	★★	★★	★★★★★	★★★★	✓	?
Semi-rotary pumps	3	5-10	★	★★	★★	★★	✓	x
Gas or vapour displacement	3	5-50	★★★★	★★★★	★★★	★★★	✓ or x	?
Rotary/continuous								
Gear and lobe pumps	3	10-20	★	★	★★	★★★	✓	x
Flexible vane pumps	3	10-20	★★	★★★	★★★	★★★★	✓	x
Progressive cavity (Mono)	3	10-100	★★★	★★★	★★★★	★★★★	x	?
Archimedean screw	3	>2	★★	★★★★	★★★	★★★	x	✓
Open screw pumps	3	>6	★★★★	★★★★★	★★★★	★★★★★	x	✓
Coil and spiral pumps	2	>6	★★	★★	★★★	★★★	x	✓
Flash wheels and treadmills	2 & 3	>2	★★	★★★★	★★	★★	x	✓
Water ladders 'dragon-spines'	2	>2	★★	★★★	★★★	★★★	x	✓
Chain (or rope) and washer	2 & 3	3-20	★★★	★★★	★★★★	★★★★	x	✓
Peristaltic pump	3	>3	★	★	★★★	★★★	✓	x
Porous rope	3	3-10	★★	★★	?	?	x	?
III VELOCITY PUMPS								
Reciprocating/cyclic								
Inertia and 'joggle' pumps	2 & 3	2-4	★	★★	★★★★	★★	x	✓
Flap valve pump	1 & 2	2-4	★	★	★★	★	x	✓
Resonating joggle pump	2	2-10	★★	★★★★	★★★★	★★★	x	?
Rebound inertia	3	2-60	★★	★	★★★★	★★★	✓	x
Rotary/continuous								
Propeller (axial-flow) pumps	3	5-3	★★★★	★★★★★	★★★★	★★★★	x	✓
Mixed-flow pumps	3	2-10	★★★★	★★★★★	★★★★	★★★★	x	✓
Centrifugal (volute) pumps	3	3-20+	★★★★★	★★★★★	★★★★	★★★	✓	✓
Centrifugal (turbine) pumps	3	3-20+	★★★★★	★★★★★	★★★★	★★★★	✓	✓
Centrifugal (regenerative) pumps	3	10-30	★★★	★★★	★★★	★★★★	✓	x
Jet pumps (water, air or stream)	3	2-20	★★★	★★★	★★	★★★	x	x
IV BUOYANCY PUMPS								
Air lift	3	5-50	★★	★★★	★★	★★★★	x	x
V IMPULSE PUMPS								
Hydraulic ram	3	10-100	★★	★★	★★★	★★★	x	✓
VI GRAVITY DEVICES								
Syphons	1, 2 & 3	1-(–10)	—	★★★★★	—	★★	—	✓
Qanats or foggara	2	—	—	★★	★★★★★	—	—	✓

Construction: 1 Basic 2 Traditional 3 Industrial

Very low ★
Low-medium ★★
Medium ★★★
Medium-high ★★★★
High ★★★★★

Yes ✓
No x

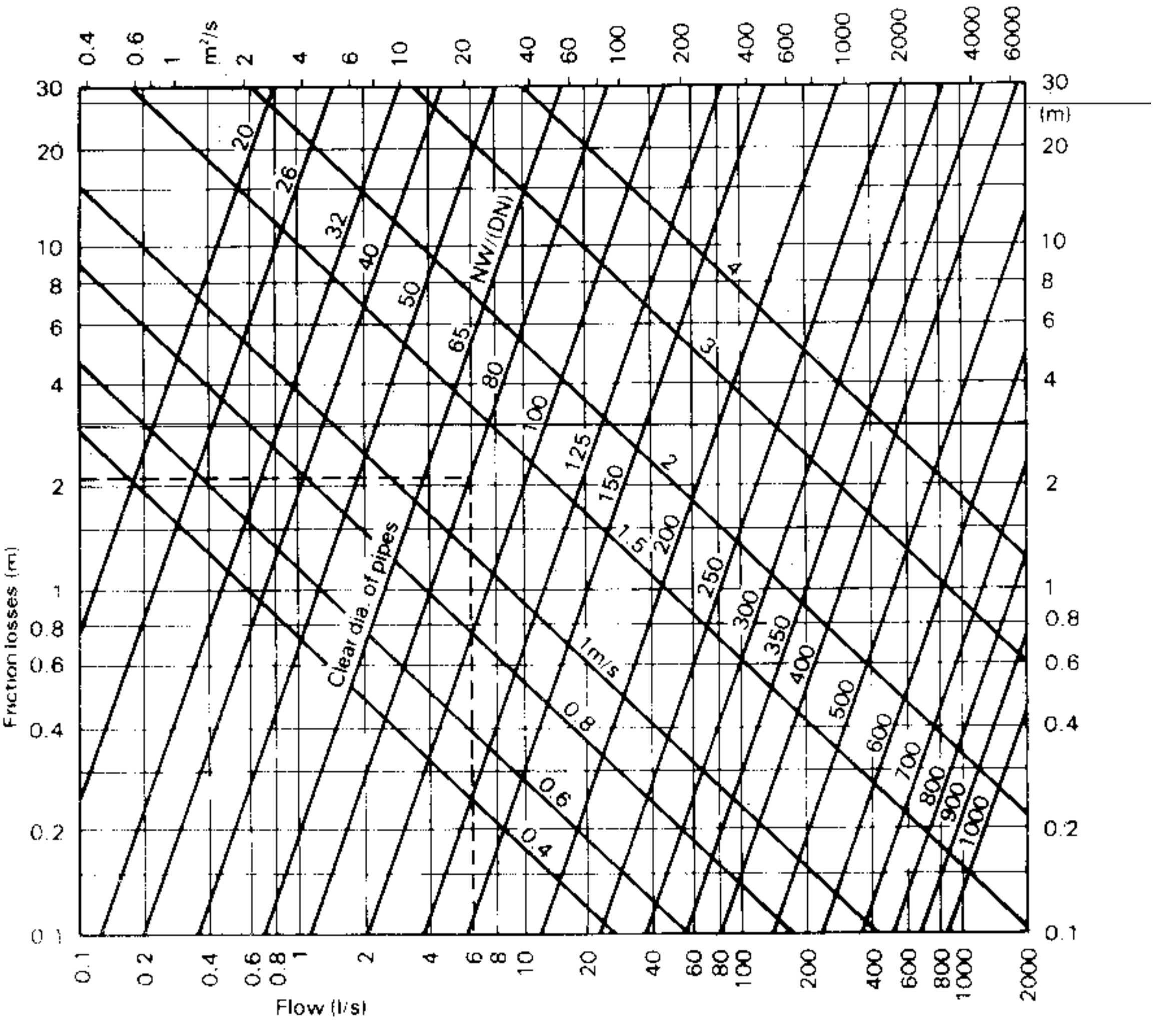
Yes ✓
Possible ?
Unlikely x

Appendix 3 Materials and tools prices in Mbarara

Price list of materials and tools from Mbarara, Uganda July /August 2000

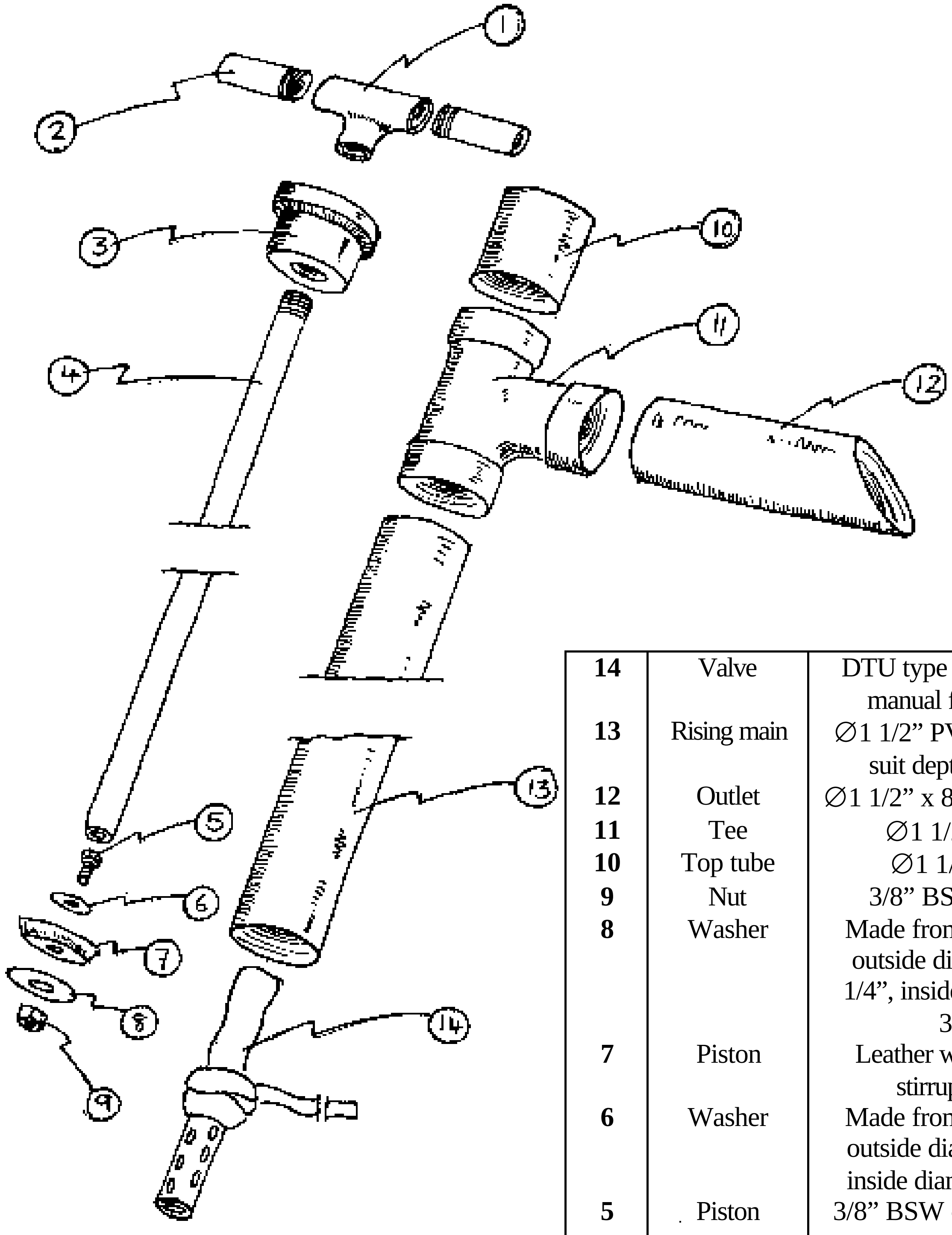
No	Item	length (feet)	value UGS	value £'s
1	Pipe PVC 1 1/4" diameter	20	11,000	4.78
2	Pipe PVC 1/2" diameter	20	7,500	3.26
3	Pipe PVC 3/4" diameter	20	10,000	4.35
4	Pipe PVC1 1/2" diameter	20	12,500	5.43
5	2" x 4 " hardwood	12	3,000	1.30
6	3" diamter GI pipe	4	5,000	2.17
7	3/4" hose pipe	1	500	0.22
8	3/4" wood chisel		13,000	5.65
9	3/8" bolts x 3"		500	0.22
10	3/8" washers		200	0.09
11	7/8" drill bit		2,500	1.09
12	Basin PVC		1,500	0.65
13	Bearing (OD = 40mm, ID = 12mm)		8,000	3.48
14	Bicycle (Indian)		80,000	34.78
15	Binding wire 1kg		2,000	0.87
16	Casual labour wages/day		3,000	1.30
17	Cement (50kg)		10,000	4.35
18	Cement (PVC) 1 tin		5,000	2.17
19	Chains	3	2,000	0.87
20	Charcoal (5ltr tin)		500	0.22
21	Cycle inner tube		2,000	0.87
22	Develop film		2,500	1.09
23	Elbow 3" dia GI		3,000	1.30
24	File 10" rough		2,000	0.87
25	Fired bricks		40	0.02
26	Guttering GI	6	4,500	1.96
27	hacksaw		2,500	1.09
28	Hacksaw blade		1,000	0.43
29	hammer & chain		3,000	1.30
30	Hammer (claw)		3,500	1.52
31	Handrill		14,000	6.09
32	Hinges (pair steel 3")		500	0.22
33	Inlets & bushes (for Harold & NZ handpumps)		267	0.12
34	Jerrycan		2,300	1.00
35	Jubilee clips (4" dia)		3,000	1.30
36	Leather washers (1 1/2" diameter)		500	0.22
37	Masons wages/day		5,000	2.17
38	Mole grips		5,000	2.17
39	Mossi net (PVC)	6	4,000	1.74
40	No 4 x 1 1/4"wood screws		1,000	0.43
41	Nuts & bolts		5,000	2.17
42	Padlock (small)		3,600	1.57
43	Pipe wrench (10")		5,000	2.17
44	Pliers		2,500	1.09
45	Rough file		2,000	0.87
46	Rubber strips	4	300	0.13
47	Screwdriver (medium flat)		3,000	1.30
48	Selotape roll 2" wide		1,300	0.57
49	Spanner (adj 10")		5,000	2.17
50	Tees 1 1/2" PVC		2,500	1.09
51	Tees 1" GI		1,500	0.65
52	Tees 1" PVC		2,000	0.87
53	Tees 1/2" GI		500	0.22
54	Tees 1/2" PVC		500	0.22
55	Tees 3/4" GI		1,000	0.43
56	Tees 3/4" PVC		800	0.35
57	Toolbox (large made from GI sheet)		10,000	4.35
58	Wood screws 1 1/2" long		2,000	0.87
59	Wood screws 3/4" long		1,000	0.43

Appendix 4 Chart for head friction losses in straight pipes



[Fraenkel, 1997, p13]

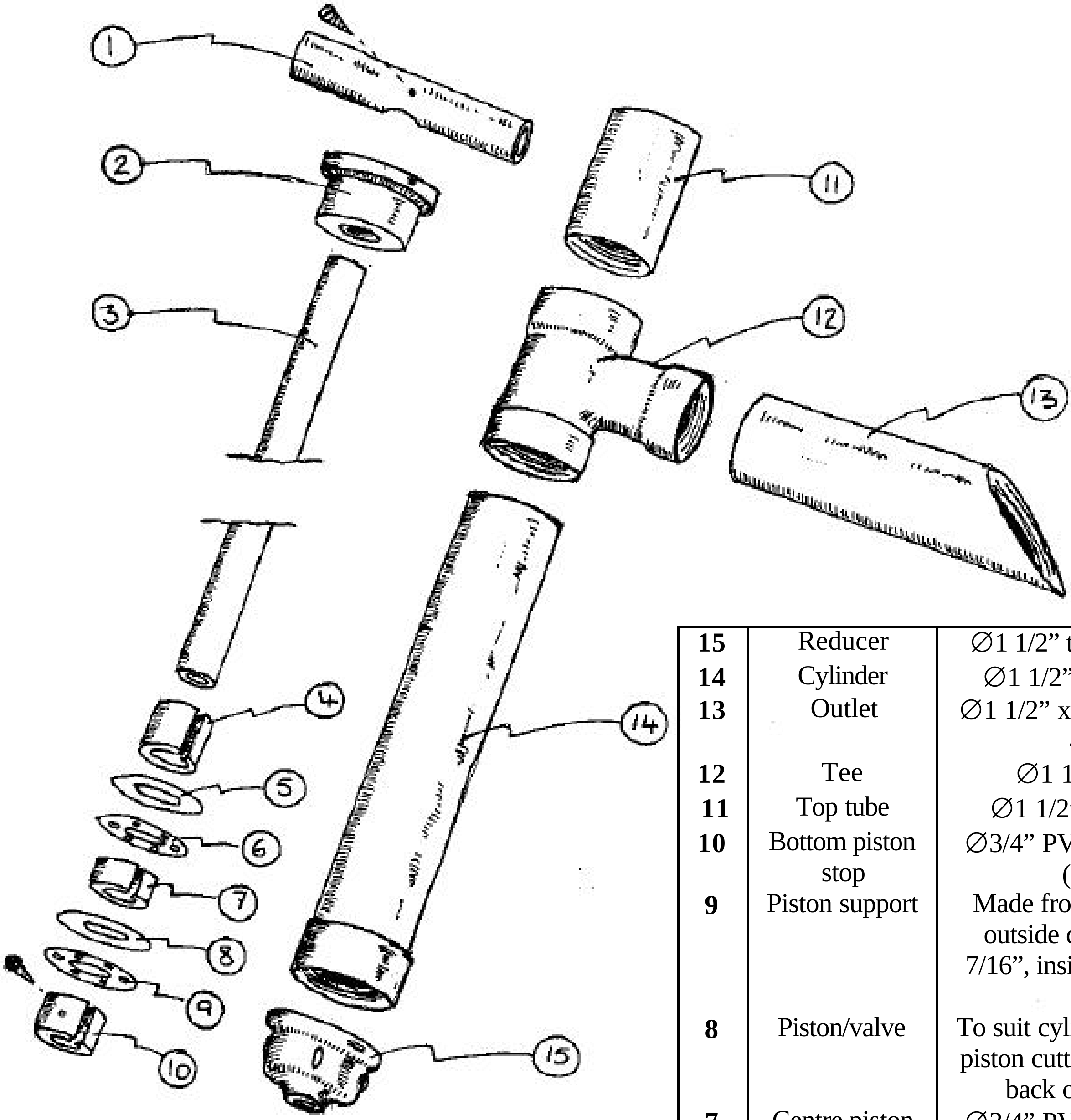
Appendix 5 DTU Handpump assembly drawing



14	Valve	DTU type (see back of manual for details)
13	Rising main	∅1 1/2” PVC (length to suit depth of tank)
12	Outlet	∅1 1/2” x 8” (end at 45°)
11	Tee	∅1 1/2” PVC
10	Top tube	∅1 1/2” x 8”
9	Nut	3/8” BSW or M8
8	Washer	Made from PVC pipe, outside diameter = 1 1/4”, inside diameter = 3/8”
7	Piston	Leather washer from stirrup pump
6	Washer	Made from PVC pipe, outside diameter = 1”, inside diameter = 3/8”
5	Piston screw	3/8” BSW or M8 x 3/4”
4	Pull rod	1/2” PVC pipe (length to suit rising main)
3	Pull rod bush	To suit pipe (see detailed drawing at back of manual for sizes)
2	Handles	1/2” PVC pipe x 4” (2 pieces)
1	Tee	1/2” PVC or GI

(Whitehead, 2000)

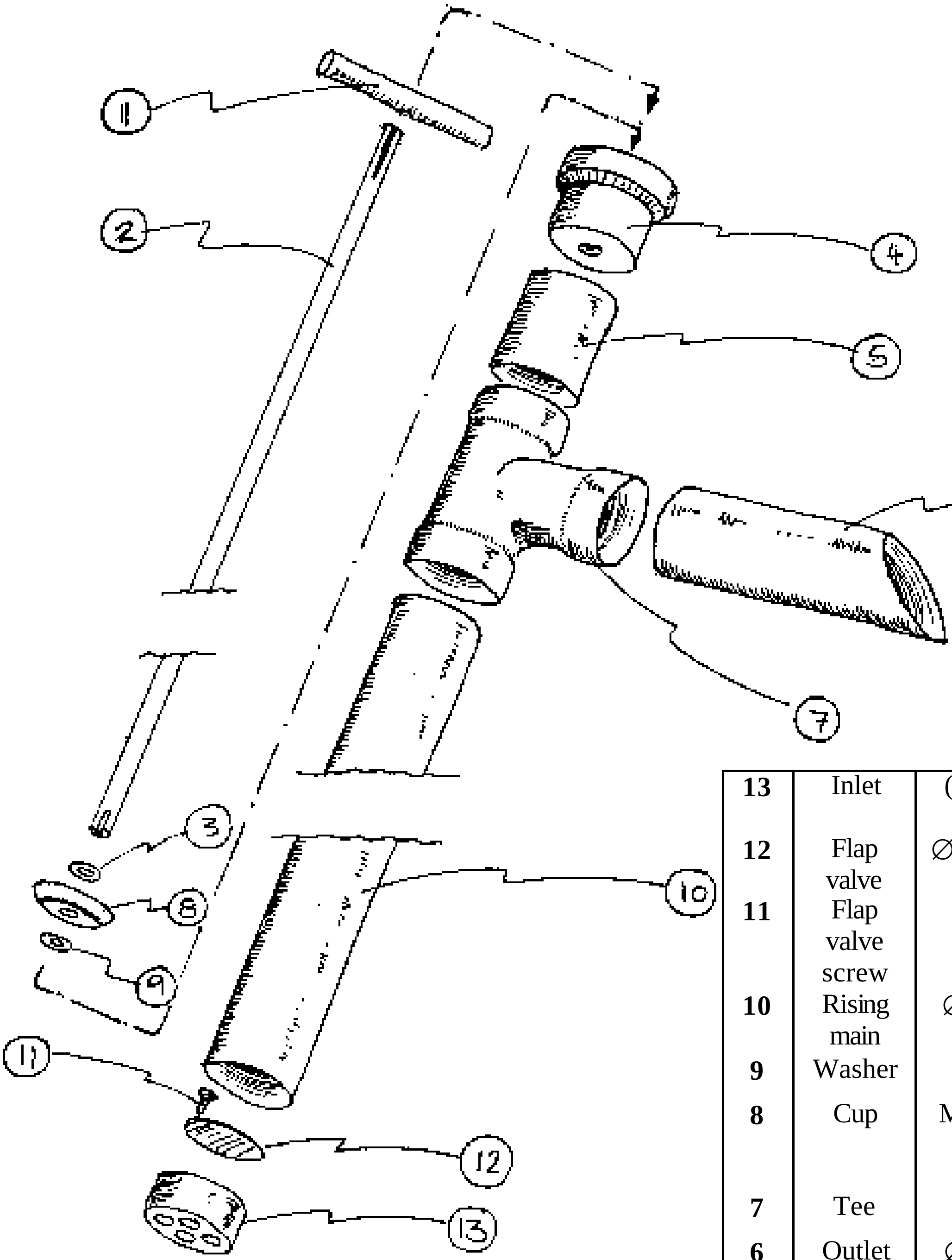
Appendix 6 Tamana handpump assembly drawing



15	Reducer	∅1 1/2” to ∅1/2” G.I.
14	Cylinder	∅1 1/2” PVC x 18”
13	Outlet	∅1 1/2” x 8” (end cut at 45°)
12	Tee	∅1 1/2” PVC
11	Top tube	∅1 1/2” PVC x 6”
10	Bottom piston stop	∅3/4” PVC pipe x 5/8” (split)
9	Piston support	Made from PVC pipe, outside diameter = 1 7/16”, inside diameter = 7/8”
8	Piston/valve	To suit cylinder bore (use piston cutter as shown in back of manual)
7	Centre piston stop	∅3/4” PVC pipe x 5/8” (split)
6	Piston support	Made from PVC pipe, outside diameter = 1 7/16”, inside diameter = 7/8”
5	Piston/valve	To suit cylinder bore (use piston cutter as shown in back of manual)
4	Top piston stop	∅3/4” PVC pipe x 5/8” (split)
3	Pull rod	∅1/2” PVC x 25”
2	Pull rod bush	To suit pipe (see detailed drawing for sizes)
1	Handle	∅3/4” PVC x 8 “

(Whitehead, 2000)

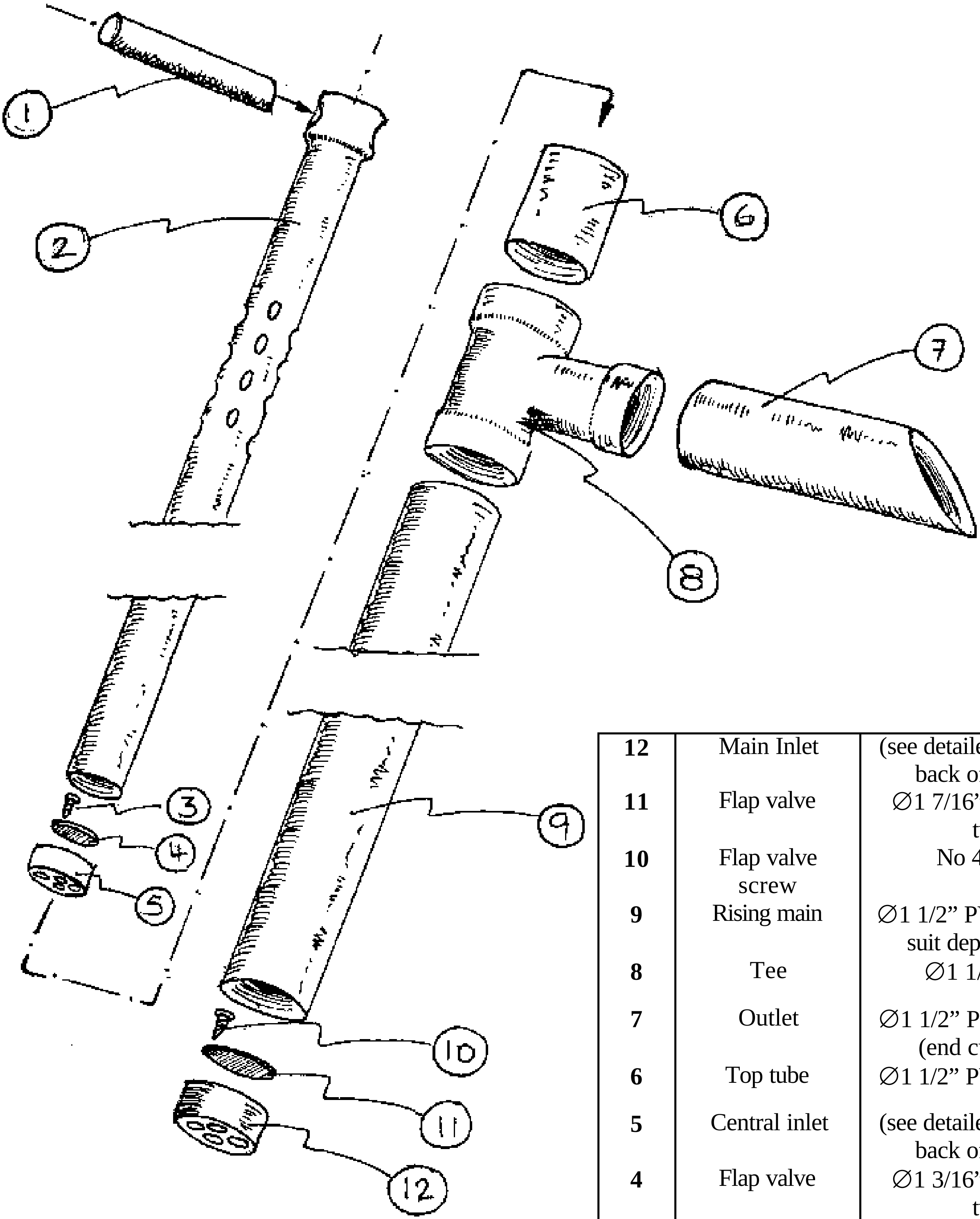
Appendix 7 Harold handpump assembly drawing



13	Inlet	(see detailed drawing in back of manual)
12	Flap valve	∅1 7/16” cycle inner tube
11	Flap valve screw	No 4 x 3/4”
10	Rising main	∅1 1/2” PVC pipe x (to suit depth of tank)
9	Washer	∅3/8”
8	Cup	Moulded PVC (see back of manual for manufacture)
7	Tee	∅1 1/2” PVC
6	Outlet	∅1 1/2” PVC pipe x 8” (end cut at 45°)
5	Top tube	∅1 1/2” PVC pipe x 8”
4	Pull rod bush	To suit pipe (see detailed drawing in back of manual for sizes)
3	Washer	∅3/8”
2	Pull rod	∅3/8” steel x (to suit depth of rising main)
1	Handle	∅1/2” PVC x 8”

(Whitehead, 2000)

Appendix 8 Enhanced Inertia handpump assembly drawing

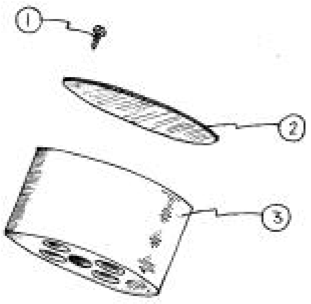


12	Main Inlet	(see detailed drawing in back of manual)
11	Flap valve	∅1 7/16” cycle inner tube
10	Flap valve screw	No 4 x 3/4”
9	Rising main	∅1 1/2” PVC pipe x (to suit depth of tank)
8	Tee	∅1 1/2” PVC
7	Outlet	∅1 1/2” PVC pipe x 8” (end cut at 45°)
6	Top tube	∅1 1/2” PVC pipe x 8”
5	Central inlet	(see detailed drawing in back of manual)
4	Flap valve	∅1 3/16” cycle inner tube
3	Flap valve screw	No 4 x 3/4”
2	Central tube	∅1 1/4” PVC pipe x (to suit rising main)
1	Handle	∅1/2” PVC x 8”

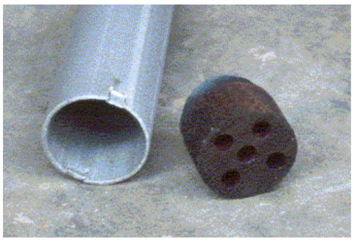
(Whitehead, 2000)

Appendix 9 Valve designs

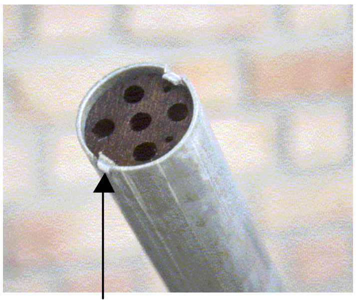
The Low Cost valve



3	Inlet
2	Flap valve
1	Screw

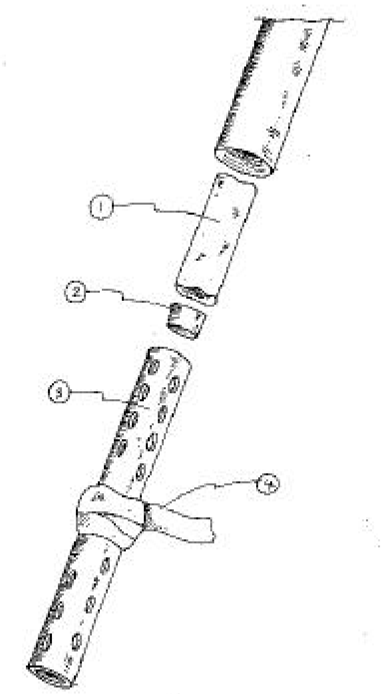


Riser pipe and valve

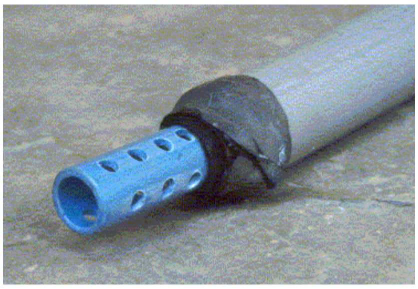


Retaining tabs bent over after fitting the valve

The DTU valve

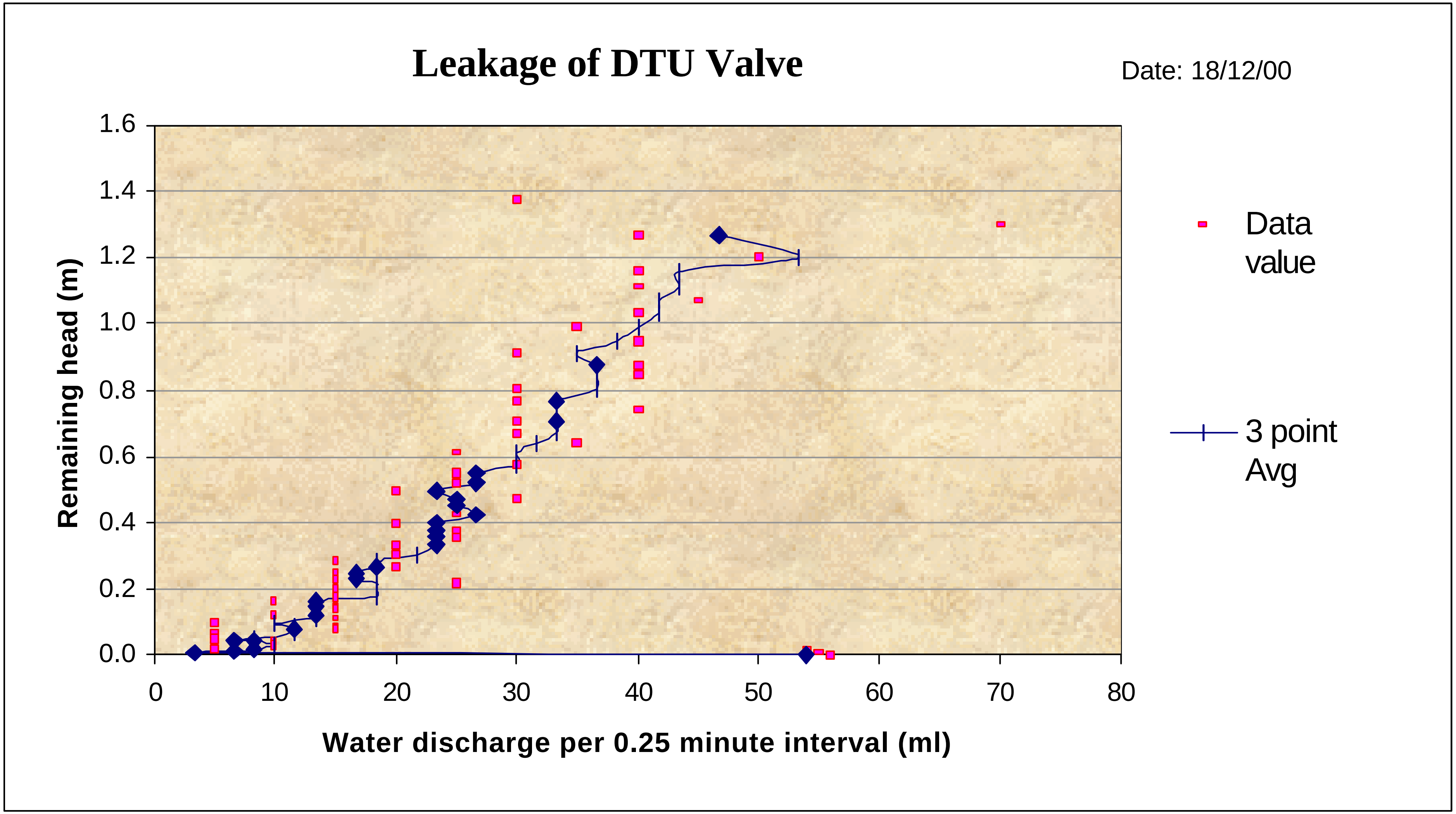


4	Rubber strip
3	Ø3/4” PVC pipe X 8” long
2	Wood plug (to suit)
1	Rubber inner tube X 4”

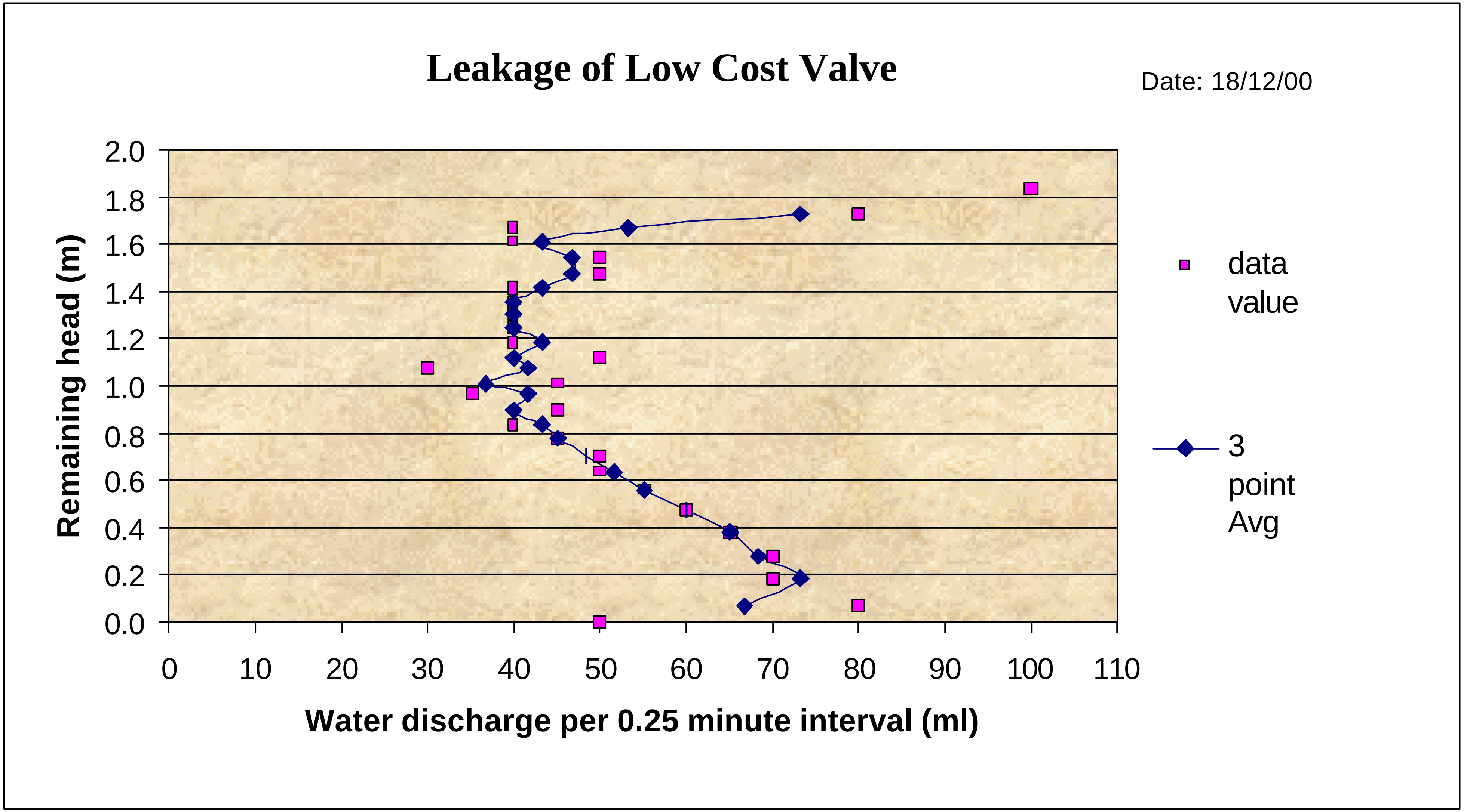


DTU valve fitted and sealed on to riser

Appendix 11 Performance test results



Appendix 11a



Handpump Performance Test No 1

Date	dd/mm/yy	18/12/00
Operator	Name	O. Beresford
Sex	m/f	m
Age	(years)	20
Heart rate at start	(bpm)	107
Handpump	Name	Harold
Molded cup size	(m)	0.035

Cadence (cycles/min)	Bore diameter of pipe (m)	Head (m)	Stroke length (m)	Time to fill 5ltr (sec)	Flow rate (ltr/min)	Volumetric efficiency	Heart rate (bpm)
40	0.036	1	0.25	72	4.2	0.41	116
40	0.036	2	0.25	62	4.8	0.48	105
40	0.036	2.5	0.25	66	4.5	0.45	108
40	0.036	1	0.365	37	8.1	0.55	114
40	0.036	2	0.365	41	7.3	0.49	111
40	0.036	2.5	0.365	45	6.7	0.45	106

Cadence (cycles/min)	Bore diameter of pipe (m)	Head (m)	Stroke length (m)	Time to fill 5ltr (sec)	Flow rate (ltr/min)	Volumetric efficiency	Heart rate (bpm)
50	0.036	1	0.25	52	5.8	0.45	114
50	0.036	2	0.25	51	5.9	0.46	118
50	0.036	2.5	0.25	46	6.5	0.51	107
50	0.036	1	0.365	26	11.5	0.62	115
50	0.036	2	0.365	26	11.5	0.62	110
50	0.036	2.5	0.365	28	10.7	0.58	106

Cadence (cycles/min)	Bore diameter of pipe (m)	Head (m)	Stroke length (m)	Time to fill 5ltr (sec)	Flow rate (ltr/min)	Volumetric efficiency	Heart rate (bpm)
60	0.036	1	0.25	36	8.3	0.55	113
60	0.036	2	0.25	33	9.1	0.60	111
60	0.036	2.5	0.25	32	9.4	0.61	109
60	0.036	1	0.365	20	15.0	0.67	115
60	0.036	2	0.365	22	13.6	0.61	112
60	0.036	2.5	0.365	22	13.6	0.61	107

Cadence (cycles/min)	Bore diameter of pipe (m)	Head (m)	Stroke length (m)	Time to fill 5ltr (sec)	Flow rate (ltr/min)	Volumetric efficiency	Heart rate (bpm)
70	0.036	1	0.25	25	12.0	0.67	113
70	0.036	2	0.25	20	15.0	0.84	115
70	0.036	2.5	0.25	26	11.5	0.65	115
70	0.036	1	0.365	15	20.0	0.77	118
70	0.036	2	0.365	16	18.8	0.72	111
70	0.036	2.5	0.365	15	20.0	0.77	109

Remarks:

highest increase of heart rate = 10 %

Operator comments:

Operator had a preference for 0.3m stroke length, and cadence of 60 cycles/min

Handpump Performance Test No 2

Date	dd/mm/yy	12-01-01
Operator	Name	M. Lyon
Sex	m/f	f
Age	(years)	24
Heart rate at start	(bpm)	89
Handpump	Name	Enhanced Inertia
Molded cup size	(m)	-

Cadence (cycles/min)	Bore diameter of pipe (m)	Head (m)	Stroke length (m)	Time to fill 5ltr (sec)	Flow rate (ltr/min)	Volumetric efficiency	Heart rate (bpm)
50	0.036	1	0.27	33	9.1	0.66	89
50	0.036	1.5	0.27	34	8.8	0.64	115
50	0.036	2	0.27	28	10.7	0.78	101
50	0.036	2.5	0.27	31	9.7	0.70	101

Cadence (cycles/min)	Bore diameter of pipe (m)	Head (m)	Stroke length (m)	Time to fill 5ltr (sec)	Flow rate (ltr/min)	Volumetric efficiency	Heart rate (bpm)
60	0.036	1	0.27	28	10.7	0.65	89
60	0.036	1.5	0.27	29	10.3	0.63	115
60	0.036	2	0.27	25	12.0	0.73	101
60	0.036	2.5	0.27	26	11.5	0.70	96

Cadence (cycles/min)	Bore diameter of pipe (m)	Head (m)	Stroke length (m)	Time to fill 5ltr (sec)	Flow rate (ltr/min)	Volumetric efficiency	Heart rate (bpm)
70	0.036	1	0.27	20	15.0	0.78	89
70	0.036	1.5	0.27	20	15.0	0.78	118
70	0.036	2	0.27	20	15.0	0.78	100
70	0.036	2.5	0.27	22	13.6	0.71	96

Remarks:

highest increase of heart rate = 33 %

Operator comments:

60Cyles was comfortable but 70 was acceptable

Handpump Performance Test No 3

Date	dd/mm/yy	17-01-01
Operator	Name	G. Still
Sex	m/f	m
Age	(years)	21
Heart rate at start	(bpm)	84
Handpump	Name	Harold
Molded cup size	(m)	0.035

Cadence (cycles/min)	Bore diameter of pipe (m)	Head (m)	Stroke length (m)	Time to fill 5ltr (sec)	Flow rate (ltr/min)	Volumetric efficiency	Heart rate (bpm)
50	0.036	1	0.25	26	11.5	0.91	84
50	0.036	2	0.25	30	10.0	0.79	90
50	0.036	1.5	0.365	29	10.3	0.56	86
50	0.036	2.5	0.365	29	10.3	0.56	89

Cadence (cycles/min)	Bore diameter of pipe (m)	Head (m)	Stroke length (m)	Time to fill 5ltr (sec)	Flow rate (ltr/min)	Volumetric efficiency	Heart rate (bpm)
60	0.036	1	0.25	24	12.5	0.82	85
60	0.036	2	0.25	25	12.0	0.79	88
60	0.036	1.5	0.365	25	12.0	0.54	88
60	0.036	2.5	0.365	27	11.1	0.50	89

Cadence (cycles/min)	Bore diameter of pipe (m)	Head (m)	Stroke length (m)	Time to fill 5ltr (sec)	Flow rate (ltr/min)	Volumetric efficiency	Heart rate (bpm)
70	0.036	1	0.25	19	15.8	0.89	90
70	0.036	2	0.25	22	13.6	0.77	86
70	0.036	1.5	0.365	22	13.6	0.52	85
70	0.036	2.5	0.365	25	12.0	0.46	96

Remarks:

highest increase of heart rate = 14 %

Operator comments:

60 cycles/min felt comfortable
Height of pump was okay

Handpump Performance Test No4

Date	dd/mm/yy	15-01-01
Operator	Name	D. Rees
Sex	m/f	m
Age	(years)	38
Heart rate at start	(bpm)	78
Handpump	Name	Enhanced Inertia
Molded cup size	(m)	-

Cadence (cycles/min)	**Bore diameter of pipe (m)**	**Head (m)**	**Stroke length (m)**	**Time to fill 5ltr (sec)**	**Flow rate (ltr/min)**	**Volumetric efficiency**	**Heart rate (bpm)**
50	0.036	1	0.2	37	8.1	0.80	76
50	0.036	1.5	0.2	45	6.7	0.65	85
50	0.036	2	0.2	46	6.5	0.64	87
50	0.036	2.5	0.2	43	7.0	0.69	80

Cadence (cycles/min)	**Bore diameter of pipe (m)**	**Head (m)**	**Stroke length (m)**	**Time to fill 5ltr (sec)**	**Flow rate (ltr/min)**	**Volumetric efficiency**	**Heart rate (bpm)**
60	0.036	1	0.2	33	9.1	0.74	80
60	0.036	1.5	0.2	37	8.1	0.66	78
60	0.036	2	0.2	35	8.6	0.70	79
60	0.036	2.5	0.2	39	7.7	0.63	85

Cadence (cycles/min)	**Bore diameter of pipe (m)**	**Head (m)**	**Stroke length (m)**	**Time to fill 5ltr (sec)**	**Flow rate (ltr/min)**	**Volumetric efficiency**	**Heart rate (bpm)**
70	0.036	1	0.2	24	12.5	0.88	78
70	0.036	1.5	0.2	29	10.3	0.73	83
70	0.036	2	0.2	32	9.4	0.66	81
70	0.036	2.5	0.2	31	9.7	0.68	81

Remarks:

highest increase of heart rate = 12 %

Operator comments:

Cadence of 60Cyles was comfortable and 70 was still acceptable

Appendix 12 Handpump questionnaire

Handpump Questionnaire

Handpump type (Harold or Enhanced inertia)

Enter today’s date:

Date or month of handpump installation:

1	Who uses the handpump mostly (tick any which apply)	Girl	Woman	Boy	Man
2	How old is the boy girl that uses the pump?				
3	Does the child find it hard to use the pump? (right height etc)				
4	How many days is the handpump used each week?				
5	How many jerricans are filled on average each day?				
6	Is the time to fill a jerrican too slow or acceptable? (if possible give the time it takes and who filled it: boy or girl etc)				
7	How hard is it for a child to use and fill a 20 litre jerrican (easy, moderate or difficult)				
8	Has it broken down since it was installed. (if the answer is no go to question 9)				
8a	If so what was the reason for the breakdown.				
8b	How long was it before it was repaired (days)				
8c	Who repaired it? (Were they trained at or by Kyera farm)				
9	What are your feelings about the handpump? i.e. What do you think is good about the handpump. Is there any improvement that could be made to the handpump? Any other comments				

Photo gallery of finished handpumps at Kyera, Mbarara, Uganda August 2000

Figure 1 A 20 litre Jerrican under the Enhanced inertia handpump installed in a plastic tube tank

Figure 2 A Harold pump cemented into a plastic tube tank at Kyera Farm

Figure 3 A Ugandan operating the Tamana handpump

Figure 4 The DTU (left) and the Tamana handpumps fitted to a partially below ground tank

Figure 3 Participants after completing the two-day 'Handpump Manufacturing Workshop' at Mbarara, Uganda August 2000.