

**DEVELOPMENT
TECHNOLOGY
UNIT**



Working Paper No 33

**Comparison Between DTU and Commercial
Hydraulic Ram Pump Performance**

Development Technology Unit, Department of Engineering,

Warwick University, Coventry CV4 7AL

Tel: (0) 203 523122 Fax: (0) 203 418922 Telex: 311904 UNIVWK G

Comparison between DTU and Commercial Ram Hydraulic Ram Pump Performances

UPDATE AND COMMENTS, APRIL 1996

Since this paper was written, the DTU Mark 6.4 pump has been phased out, to be replaced by first the M8.4 and more recently the S2. All these are pumps normally run with a 2" G.I. drivepipe and delivering to up to 100m using a drive flow of 40 to 120 litres/min. Preliminary results for the M8/S2 on a single setting are given at the end of this paper, indicating that, setting for setting, the M8 is superior to its predecessors. Generally the DTU later models are more efficient than the M6. Of course performance as measured in this paper is only part of the story. The DTU pumps are made largely of mild steel and are therefore more subject to corrosion than most 'commercial' machines. In recent years there has been a trend towards use of plastics in ram pumps as pvc or ABS piping replaces galvanised iron. However plastic pumps can rarely operate reliably at delivery heads exceeding 40 meters. There is also a growing interest in providing the air-cushioning of the output via an enclosed air packet (for example closed cell foam) instead of an air vessel with a free air-water surface. This arrangement can effectively increase the usable drive head by allowing the impulse valve exhaust to emerge under water.

In the paper, the early comparisons with commercial pumps use data from a study by T H Delft which were obtained from slightly larger models (from the respective manufacturers' ranges), and with a much higher drivehead, than the comparisons in the rest of the paper.

Details of the current (1996) DTU designs, namely S1 (for use with a 1" steel drivepipe), S2 (2" steel) and P90 (90 mm. pvc) are given in DTU Technical Releases TR11, TR14 and TR12 respectively.

CONTENTS	Page No.
1. INTRODUCTION	1
1.1 Delft University	1
1.2 DTU, University of Warwick	1
2. SUMMARY OF WORK CARRIED OUT AT DELFT	
2.1 Selection of Pumps	2
2.2 Assessment of Experimental Procedure	4
2.3 Summary of Results	6
2.4 Conclusions about Commercial Pumps	7
2.5 Non-Dimensional Comparison	10
3. SUMMARY OF DTU TESTS	
3.1 Experimental Rig and Procedure	10
3.2 Pump Tuning	10
3.3 Summary of Test Results	12
4. COMPARISON OF DTU AND COMMERCIAL PUMPS	
4.1 Problems in Comparison	17
4.2 Efficiency Comparisons	17
4.3 Power Comparison	19
5. COST COMPARISON	19
6. SUMMARY OF CONCLUSION	22
Appendix A CONTINUING DTU PUMP DEVELOPMENT	25
Appendix B TABLES OF PERFORMANCE RESULTS	28
Appendix C FURTHER NOTES AND COMMENTS ON THE WORK AT DELF	33

List of Tables

Page No.

Table 1	Comparison of Commercial Hydraulic Rams	3
2	Cost Comparison of Commercial Rams	4
3	Hydraulic Rams Selected by Delft	5
4	Summary of Delft Test Results	6
5	Summary of DTU M6.4 Test Results	7

List of Graphs

Graph 1	Efficiency of Commercial Pumps	8
2	Power of Commercial Pumps	9
3	Ratio of Commercial Pumps	11
4	Efficiency of DTU M6.4	14
5	Power of DTU M6.4	15
6	Ratio of DTU M6.4	16
7	Efficiency Comparison of DTU with Commercial Pumps	18
8	Power Comparison of DTU with Commercial Pumps	20
9	Ratio Comparison of DTU with Commercial Pumps	23
10	Efficiency Comparison of M6.4 and M8.4	26
11	Power Comparison of M6.4 and M8.4	27

List of Figures

Figure 1	DTU experimental rig	12
----------	----------------------	----

1. INTRODUCTION

This paper details the performance of the DTU Mark 6.4 hydraulic ram pump in comparison to commercial models run under similar conditions. Details of the performance of a number of commercial pumps tested at Delft University, Netherlands are used for comparison.

1.1 Delft University

Between 1982 and 1984 J. Tacke of Delft University of Technology carried out tests on a number of commercially available hydraulic ram pumps. These were published in 1988 with comprehensive details of all results obtained and the development of a mathematical model for prediction of ram performance. As part of this programme field tests were conducted by the Foundation of Dutch Volunteers in Rwanda. These aimed to investigate the technical performance and durability under operating conditions in a community setting, social acceptance and community participation in installing, operating and maintaining a hydraulic ram system.

The presentation by Delft of all laboratory test results is excellent and allows a good level of comparison for tests on subsequent designs. Unfortunately no details of the findings or conclusions resulting from the field trials in Rwanda are made available. However the DTU are greatly indebted to Delft for their provision of such a useful resource.

1.2 DTU, University of Warwick

The Development Technology Unit has been investigating hydraulic ram pump design, performance and manufacture since 1985. This began with student projects and has grown into a full-time research programme largely funded by the Overseas Development Administration. The aims of the programme are:

- a) to analyse in detail the operation of the ram pump gaining a comprehensive understanding of the operating principles and complex hydraulic interactions occurring within the pump.
- b) to produce pump designs suitable for manufacture in developing countries using available materials and production processes.
- c) to thoroughly test such designs for their performance and endurance (including extensive field trials) and offer findings for widespread dissemination.
- d) to develop and prove methods for surveying and design of complete water supply installations.
- e) to produce design charts and computer based tools to enable design and field engineers to confidently include hydraulic ram pumps as an option in their water supply schemes.
- f) to provide technical expertise and training for two African based programmes installing ram pumps for village water supply and irrigation.

In terms of hardware development the DTU has two distinct working areas. The first is the development of designs of steel hydraulic ram pumps based on the 2" diameter BSP pipe that has been found to be widely available in developing countries and is of an appropriate capacity for small village water supply schemes. The second area of hardware development is the production of plastic hydraulic ram pumps based on widely available 110mm plastic pipe and especially suitable for irrigation close to water courses. Rough specifications and performance indications are given below.

Materials required	Steel	Plastic
	2" Galvanised pipe	110mm PVC pipe
	2" Fittings	Small amount of
	Mild steel bar	mild steel parts

Manufacturing process

Welding	Hand tools
Drilling	
Turning	

Typical performance ranges

	40-140	
Drive flow	40/140 l/min	200-350 l/min
Drive head	2-25m	0.5-2.5m
Delivery flow	2-12 l/min	2-25 l/min
Delivery head	up to 150m	up to 15m
Efficiency	50-90%	20-60%
Expected life	10 years	3 years

This paper is concerned solely with the comparison of the 2" steel pump with its commercially available rivals. Such pumps have found the widest application to date in supplying water for domestic use.

During the research many designs of ram pump have been produced and tested. In 1990 a design was chosen as having proven itself sufficiently in terms of performance and durability to set a 'benchmark' against which furthest developments could be assessed. It is this model, Mark 6.4, that is used in the following comparison against commercial designs.

2. SUMMARY OF WORK CARRIED OUT AT DELFT

2.1 Selection of Pumps

Delft decided to select 12 rams from 6 manufacturers that were applicable in typical village or domestic water supply schemes. In all, details of pumps from 10 manufacturers were obtained and selection made based on the following criteria:

- a) as many types of ram design as possible should be included.
- b) tests should include both traditional and modern designs.
- c) rams should show a reasonable price to performance ratio.

To enable the latter of the criteria, manufacturers were sent a set of conditions and asked to provide details of the pump they would recommend and its expected output and efficiency.

Table 1 shows the results of this comparison.

TABLE 1 - COMPARISON OF HYDRAULIC RAMS

Arrangement: Source Supply = 90 l/min
 Supply Head H_s = 7.50 m
 Delivery Head h_d = 75 m

Type of Hydraulic Ram	Drive Pipe [inch]	Pipe [mm]	Volume of Driving Water Required [l/min]	Pumping Rate q [l/min]	Efficiency η [%]	Approx Price for Ram Alone [US\$-1982]
Vulcan 2 1/2	2	65	36-114	6.10	68	1200
Blake Hydram 3 1/2	2	65	45- 96	6.00	67	1000
Sano No. 5/65 mm	2	65	50-110	6.95	77	1000
Rife 20 HDU	2	50	38- 95	5.40	60	1100
Schlumpf 5A23	2	50	50-100	5.50	61	2700
Alto CH 66-110-18	2	65	50- 90	5.40	60	2100
Briau D4	2	50	45- 90	5.40	60	3200
CeCoCo - H50	2	50	25-115	6.90	77	3500
WAMA No. 6	2	65	60-100	4.50	50	1500
BZH-Ram W6	2	65	45- 90	2.70	30	1200

Delft concluded that in terms of performance, the choice should favour the first eight pumps and of these the first six provide the best performance to price ratio. From the information given the choice seems to be a reasonable one.

An alternative comparison to evaluate the performance to price ratio would have been to include a cost per litre delivered under these conditions. This significantly alters the ranking of pumps as is shown in Table 2.

TABLE 2

Type of Hydraulic Ram	Pumping Rate q [C/min]	Efficiency (Trade) (%)	Approx Price for Ram Alone [US\$-1982]	Cost per litre delivered	Rank
Vulcan 2½	6.10	68	1200	197	3
Blake Hydram 3½	6.00	67	1000	167	2
Sano No. 5/65 mm	6.95	77	1000	144	1
Rife 20 HDU	5.40	60	1100	204	4
Schlumpf 5A23	5.50	61	2700	491	8
Alto CH 66-110-18	5.40	60	2100	389	6
Briau D4	5.40	60	3200	593	10
CeCoCo - H50	6.90	77	3500	507	9
WAMA No. 6	4.50	50	1500	333	5
BZH-Ram W6	2.70	30	1200	444	7

It would also have been interesting to include details from rams currently manufactured in developing countries. Details of the rams selected are given in Table 3.

2.2 Assessment of Experimental Procedure

The tests conducted were fairly comprehensive with each ram being observed for approx. 1 month. The test rig employed allowed a supply head of between 0.5 and 3.0 m with a drive pipe length of 12m. Such a low drive head range is clearly the product of laboratory limitations and does not reflect typically observed ranges in the field of 2 to 20m.

Flows were measured by collecting water for a timed period and weighing it. For each setting this was repeated a number of times to give a more accurate average flow. This is potentially a very accurate method of flow measurement but is open to numerous experimental errors. However it does avoid the need to use flow meters that have their own inaccuracies despite careful calibration.

The designs of ram pump tested exhibit a number of different types of impulse valve. Four of the six have traditional valves above the axis of the pump body but the Schlumpf has its valve below the axis. No mention is made in the text of the Delft work as to where the supply head was measured from. To allow accurate comparison the head should be taken from the orifice of the impulse valve, not the axis of the pump body. In reality both the SANO and Schlumpf pumps may in some situations be able to utilise a given supply head more effectively by their impulse valve design.

TABLE 3 - HYDRAULIC RAMS SELECTED

Type of Hydraulic Ram	Manufacturer	Drive Pipe Diameter [ins] [mm]	Intake capacity [l/min]	Description
Blake Hydram No. 2	John Blake Ltd	1.5 40	12-25	A well-established standard design made of cast-iron. Both waste valve and delivery valve consist of a rubber disc covering a perforated gunmetal seat.
Blake Hydram No. 3.5	England	2.5 65	45-96	
Alto J 26-80-8	J.M. Desclaud	1 25	8-15	A recently renewed pump design made of steel pipe components, but using conventional valve designs. Weight-loaded gunmetal waste valve; spring-loaded rubber clack as delivery valve.
Alto CH 50-110-18	France	2 50	30-60	
Vulcan 1"	Green & Carter	1 25	4-18	A standard design made of cast-iron; like the Blake Hydram available for a long time. Both waste valve and delivery valve consist of a rubber disc covering a grid shaped, gunmetal seat.
Vulcan 2"	England	2 50	23-46	
SANO No. 1-25 mm	Pfister + Langhanss Germany	1 25	6-16	A rather unconventional' design, nowadays made of fire zinc-coated steel. Both waste valve and delivery valve are spring-act- ted and substantially made of gunmetal.
SANO No. 4-50 mm		2 50	30-65	
Davey No. 3	Rife Hydr. Eng	1 25	5-15	Rife: a fairly standard design made of cast-iron. Weight-loaded rubber waste valve, mounted on a rocker-arm; delivery valve is a rubber disc covering a grid iron seat. Davey: less efficient, less expensive low base configuration, using a weight-loaded gunmetal waste valve and a weight-loaded leather washer as delivery valve.
Rife 20 HDU	Mfg. Co.	2 50	38-95	
Schlumpf 4A5	Schlumpf Ag	1.5 40	30-60	A design available in 2 models. Model A23 uses a spring-loaded rubber waste valve mounted on a rocker and a weight-loaded rubber washer as delivery valve. The less efficient model A5 uses a weight-loaded rubber waste valve.
Schlumpf 4A23	Maschinenfabrik Switzerland	1.5 40	30-60	

The laboratory experiments also included the use of piezo-electric pressure transducers, displacement transducers and strain gauges to observe in detail the changes occurring. Although the resolution of these observations is low they are well presented and provide useful insights into pump operation.

The major criticism of the information presented by Delft is that they supply no indication of how each pump was setup when the results were taken. They simply state that 'waste valve adjustment' was 'kept constant' over the whole range of tests. To ensure a fair comparison the waste valves were presumably initially adjusted to the manufacturers recommendation that would give the best overall performance (efficiency and power output) under typical operating conditions. If this was not the case then the results are practically worthless as some of the pumps may have been badly tuned whilst others were well tuned for the given operating conditions.

2.3 Summary of results

The results presented by Delft are comprehensive within the limitations of their test rig. Delft provide data for 3 supply heads for each pump over a range of delivery heads. Of these the highest (3m) has been taken as being the most representative and all results presented below are for this fixed supply head. Table 4 shows some results for efficiency and power at typical supply to delivery head ratios.

TABLE 4 SUMMARY OF TEST RESULTS

Pump	Efficiency (%)			Power (Watts)		
	at 30m	at 60m	max	at 30m	at 60m	max
Blake No 2 (1½")	70.5	67	70.5	15.2	12.8	15.1
Blake No 3½ (2½")	72.5	68	73	38.2	12.8	15.1
Alto (1")	29	-	47	2.2	-	4.3
Alto (2")	41	23	42	10.3	3.4	7.3
Vulcan (1")	58	58	59	5.1	3.9	4.8
Vulcan (2")	75	55	77	15.2	5.9	15.9
SANO No 1 (1")	64	57	67	3.4	2.9	4.0
SANO No 4 (2")	67	66	69	20.6	19.6	20.2
Davey No 3 (1")	54	-	60	3.4	-	4.7
Rife 20H DU (2")	43	48	48	19.1	19.6	12.7
Schlumpf 4A5 (1½")	-	-	62	-	-	15.2
Schlumpf 4A23 (1½")	43	15	62	8.8	2.0	17.2

Five of the pumps tested are of similar specification to the DTU models and were therefore selected for analysis and comparison. Graphs 1 and 2 show power and efficiency curves for these five pumps. The large variations between pumps can be seen quite clearly and comparison is complicated by the marked differences in the power and efficiency curves. At low heads for instance the Vulcan 2" ram is the most efficient but has the lowest output power and will only run up to a delivery head of 85 m.

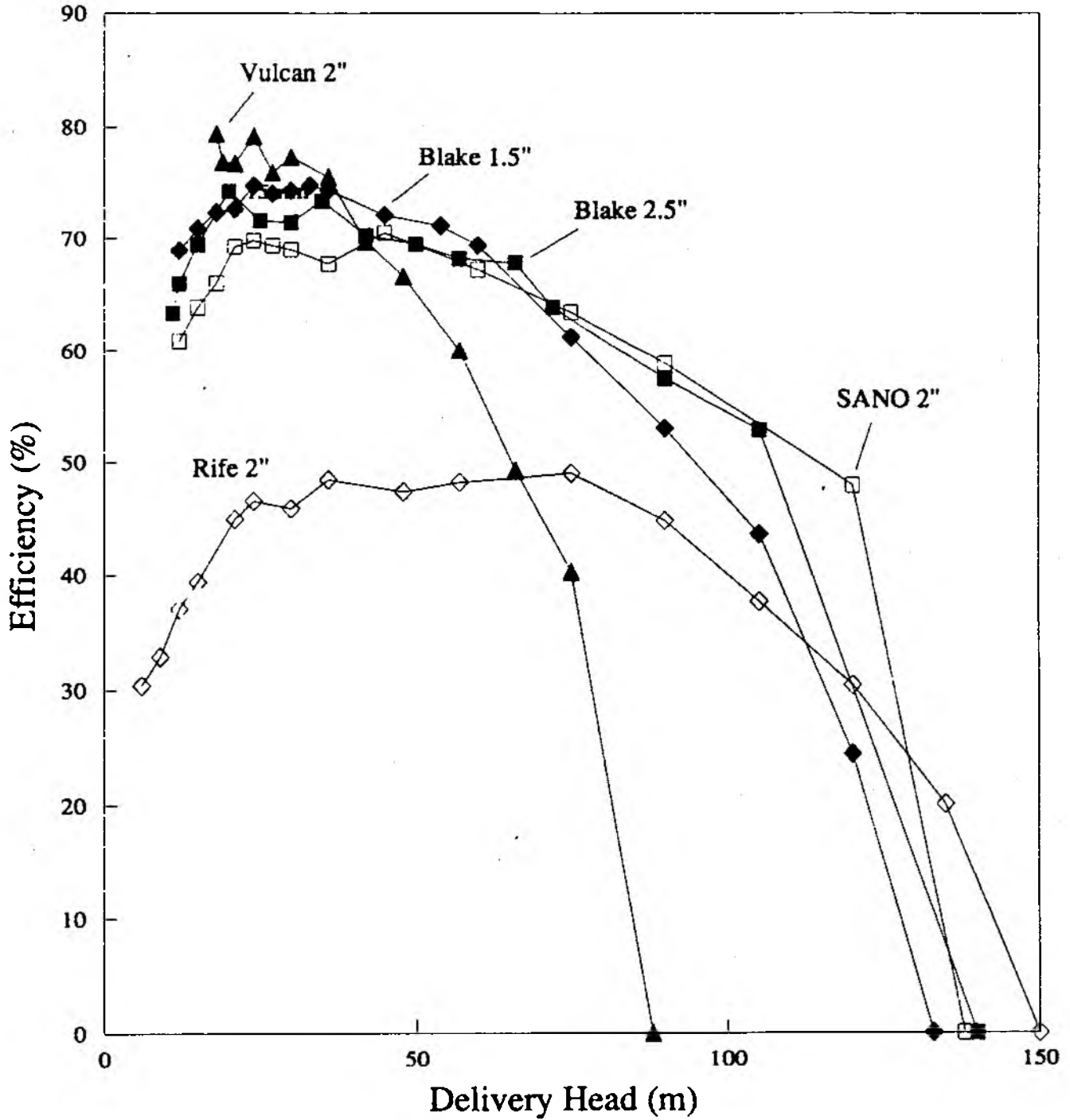
2.4 Conclusions about commercial pumps

Delft offer no conclusions or direct comparisons between the various pumps tested. The results are complex and comparison has to be based on many factors in order to produce sensible recommendations. In any given situation the exact requirements will vary. The points given below are an attempt to pick out the main items in order to draw some conclusions.

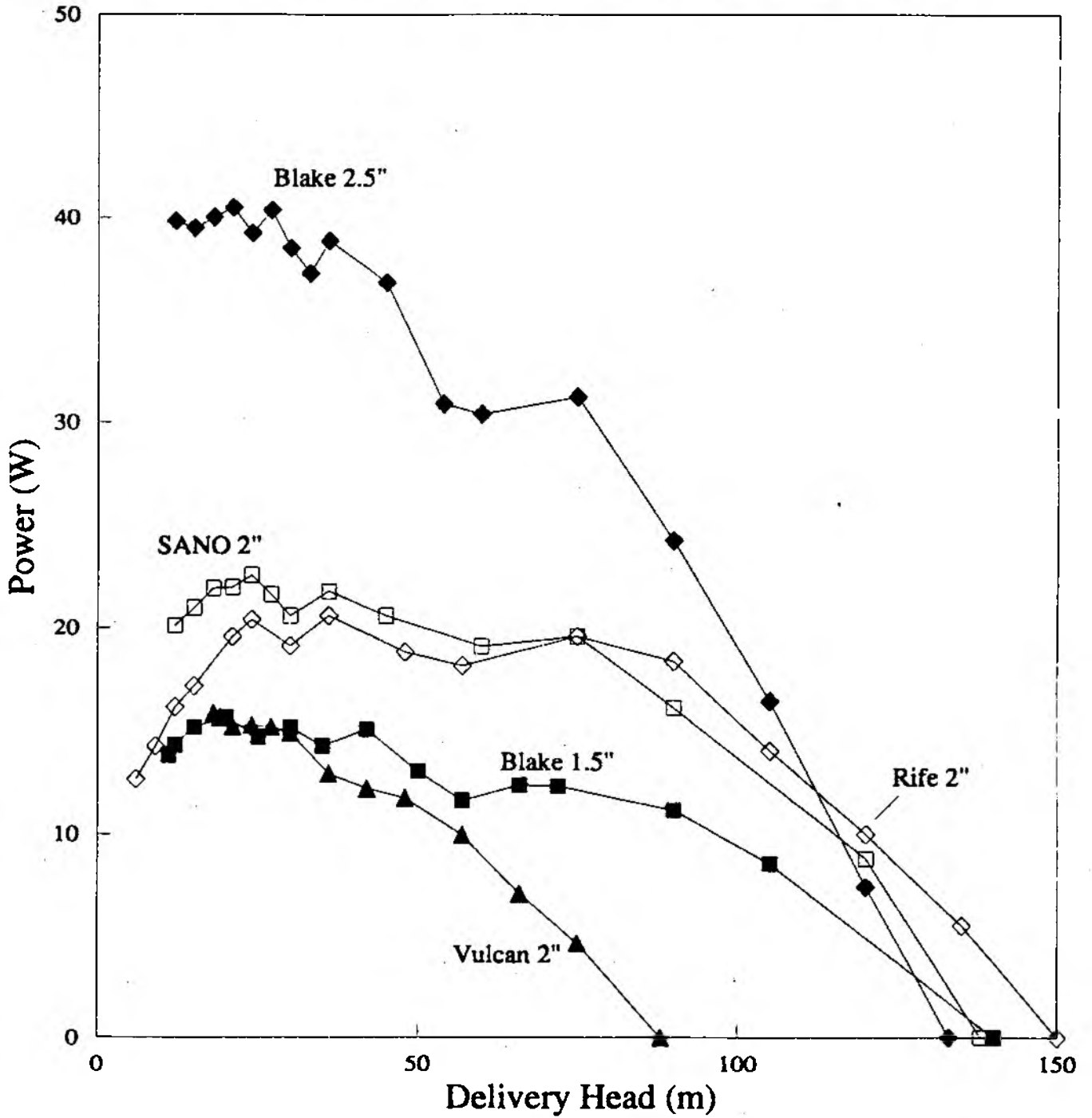
- 1) The Vulcan 2" has the highest efficiency recorded at 76.9% and at low heads (up to 36 m) has the best efficiency of all the pumps.
- 2) The Rife 2" has the lowest efficiency up to 70 m and never increases over 50%. However it has the widest range of delivery heads over which it will operate. Overall it would be fair to say that the Rife pump has the poorest efficiency.
- 3) Overall the Blake 2½" is the most efficient closely followed by the smaller Blake 1½". They show good efficiencies over the normal operating range and will pump over a wide range of delivery heads.
- 4) Similarly the SANO 2" shows good efficiencies over a wide range of delivery heads and is more efficient than the Blake pump over about 75 m.
- 5) The Vulcan 2" has the lowest power output over its small range of delivery heads.
- 6) Blake 2½" is clearly the most powerful pump over its entire range.
- 7) At low delivery heads (up to 75 m) the SANO 2" has a slightly higher output than the Rife 2" which above 75 m is better. However there is little to choose between them over the complete range of operation.
- 8) Attempting to combine both power and efficiency it would seem reasonable to conclude that the Blake 2½" offers the best overall performance. Of the remainder the SANO 2" would seem to be the best compromise.

GRAPH 1

Efficiency of Commercial Pumps



Power of Commercial Pumps



2.5 Non-Dimensional Comparison

Delft use a further means of pump comparison by graphically presenting the ratio of delivery to supply flow (q/Q) over a range of delivery to supply head (h/H) ratios. Thus a non dimensional comparison between pumps is possible. For any given head ratio the greater the ratio of flows the better the performance of the pump. Graph 3 shows these ratio curves for the five pumps chosen. Only two conclusions can sensibly be drawn from this comparison:

- 1) The Rife 2" is notably worse than all its rivals.
- 2) There is little to choose between all of the other makes of pump.

Despite this lack of obvious conclusions the ability to compare pumps using non dimensional parameters may prove valuable.

3. SUMMARY OF DTU TESTS

3.1 Experimental rig and procedure

The DTU has established performance testing rigs at the University to allow comprehensive analysis of prototype pumps. The major restrictions imposed by the rigs location are:

- i) drive pipe length - limited to 10.5 m and horizontal
- ii) drive head - restricted to 2, 3, 4 or 5 m

The delivery head is controlled using a needle valve providing an accurately variable orifice over which the desired head can be dropped (measured by a pressure gauge). Both drive and delivery flows are measured by float type flow meters for fast and accurate readings.

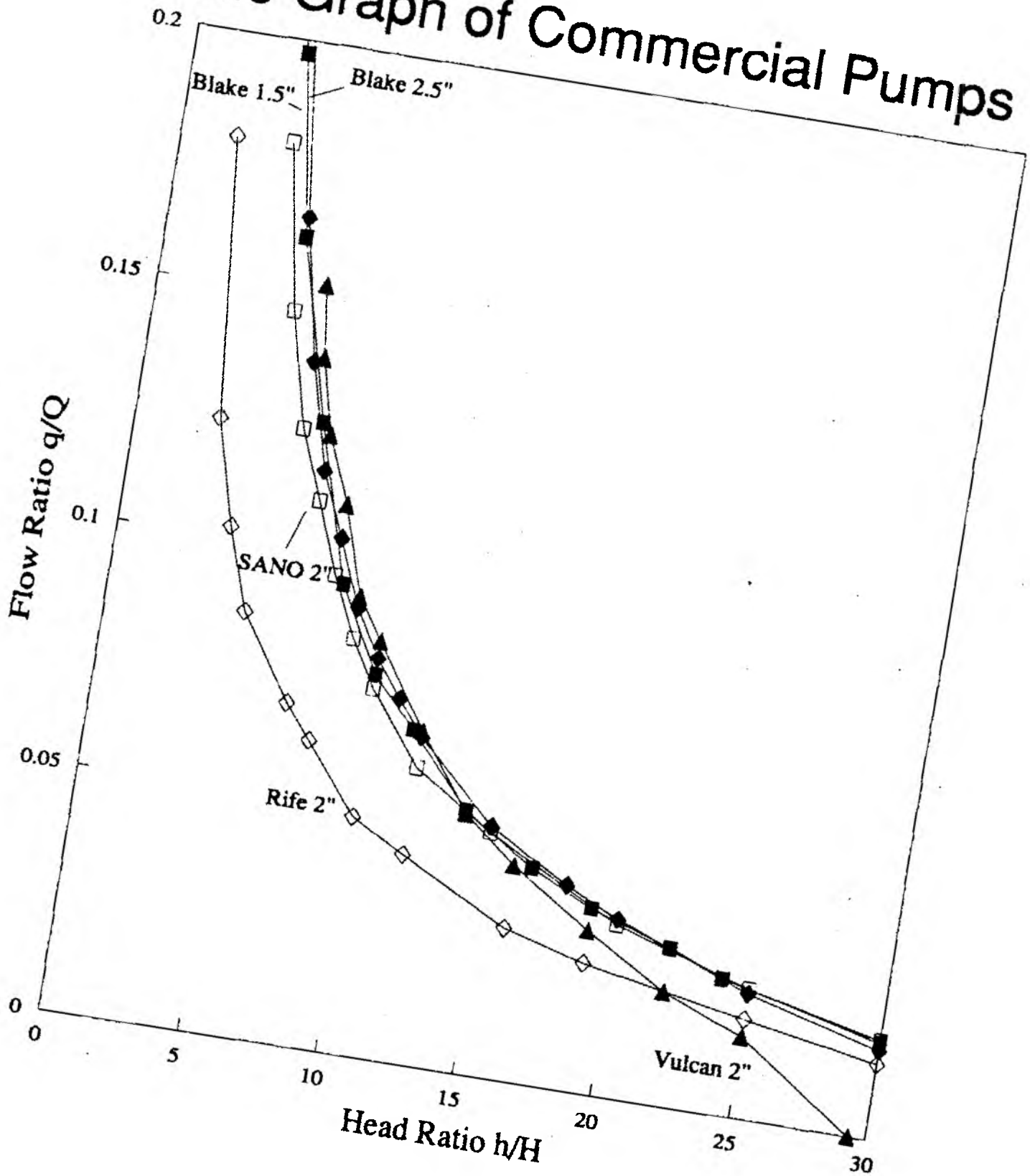
For their tests Delft used three drive head setting, 1, 2 and 3 m. However for comparison between DTU and commercial pumps only one drive head was chosen (3.0 m).

3.2 Pump Tuning

The DTU pump design selected for testing was the Mark 6.4 which typically uses a 2" BSP drive pipe but also runs using 1½" pipe (see Figure 1). As the Delft work gives no clear indication of how pumps were tuned a series of results were recorded using different settings of the impulse valve. Low stroke, low weight settings generally give high efficiency and low power output. Up to a point it is also true to say that high stroke,

GRAPH 3

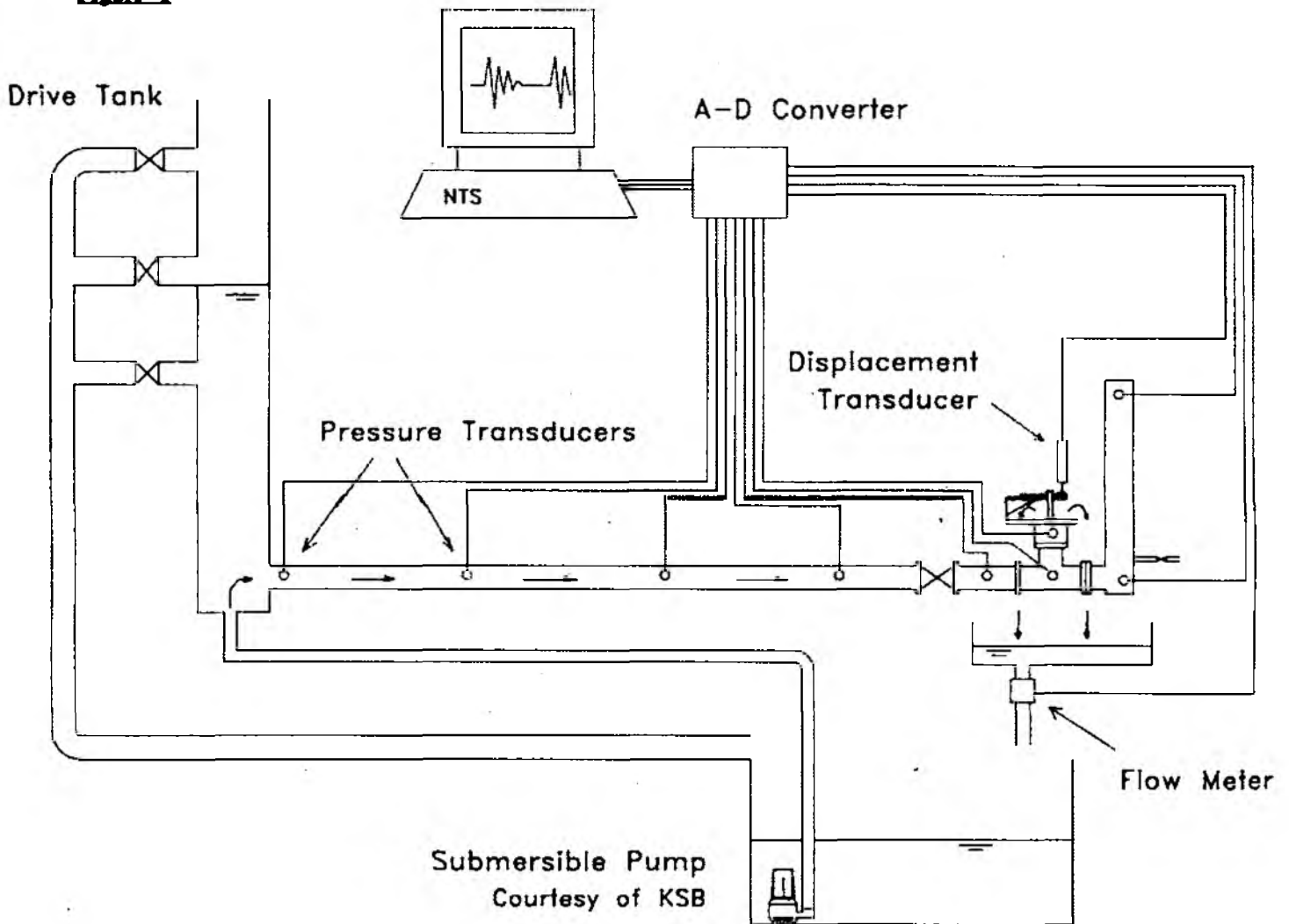
Ratio Graph of Commercial Pumps



high weight settings give low efficiency and high output power.

Choosing which of these results are used to compare against the Delft ones is dealt with in Section 4.1.

Figure 1



3.3 Summary of test results

Table 5 gives a selection of results for identical conditions as those in Table 4 for the commercial pumps.

Graphs 4 and 5 show the variation in efficiency and power over the full range of potential delivery heads.

Graph 6 presents the non dimensional flow ratio to head ratio curves for these results.

The design of the M6.4 pump allows it to be tuned to suit a wide range of flow and head conditions, making one model applicable to many sites. The results show the wide range of efficiency and power obtainable under these given conditions and emphasize how important tuning can be. If drive water is limited then peak efficiency will be required to make best use of that available. If there is plenty of drive water pumps should be tuned to give maximum power output despite the lower efficiency of such a setting.

It is clear that both good efficiency and power are obtainable over a broad range of delivery heads and that the pump is capable of operating at very high head ratios.

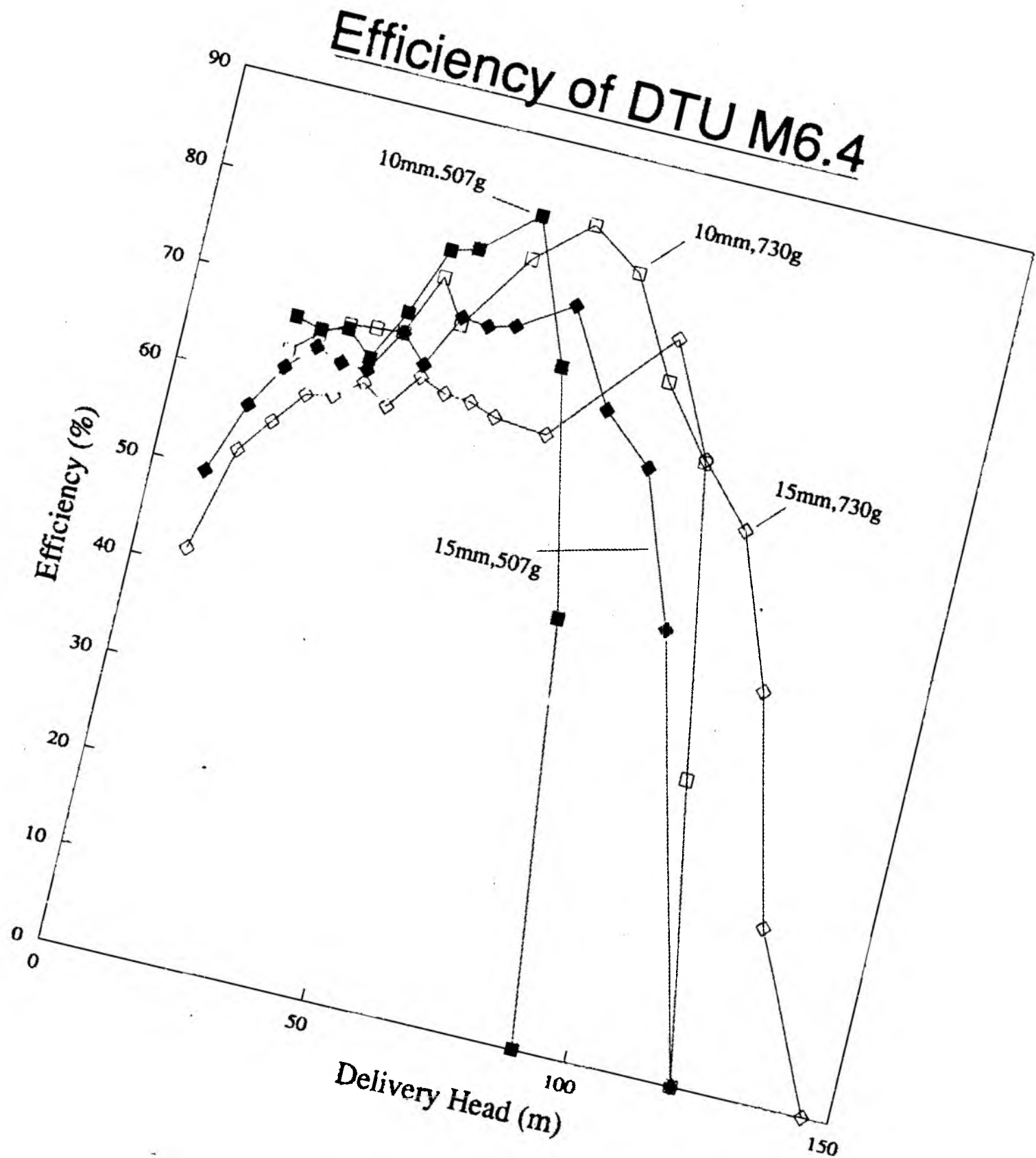
The stroke of the M6.4 design can range between 5 mm to 40 mm with infinite adjustment between these limits. The minimum weight of the valve assembly is 507g comprising the plug, stem, nuts etc. although recent modification to the pump enables further reduction. Maximum weight is limited by the physical dimensions but 1000g should be considered as the upper limit.

The results show for just a few combinations of stroke and weight how the efficiency and power output characteristics of the pump can be dramatically altered. Low stroke and weight give high efficiency but low power over a limited range of delivery heads whereas high stroke and weight give lower efficiency but high power output over a wider possible range of heads. Tuning of the pump to best suit any particular set of conditions is a complicated process to explain and is dealt with in other DTU literature.

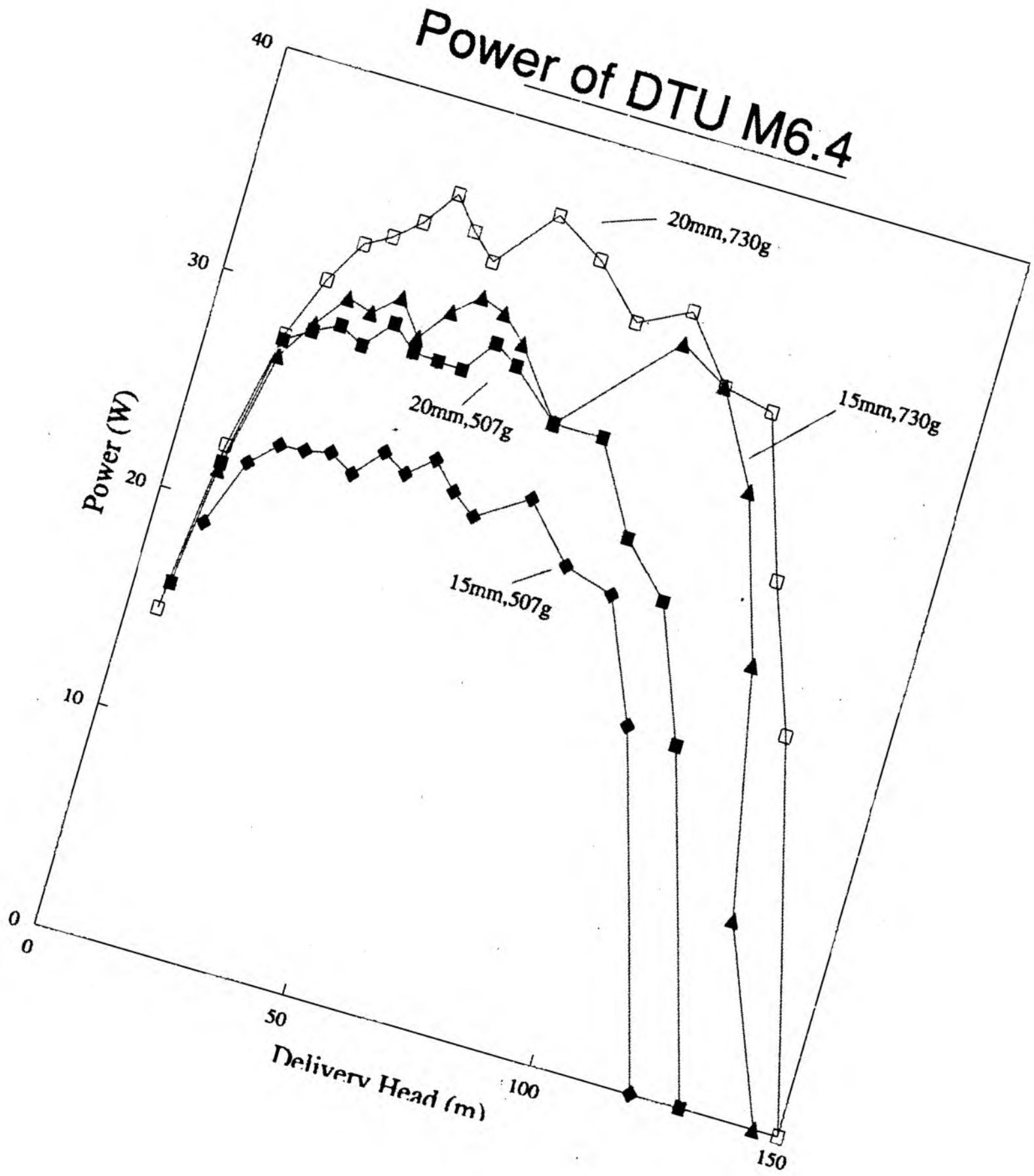
TABLE 5 SUMMARY OF DTU M6.4 TEST RESULTS

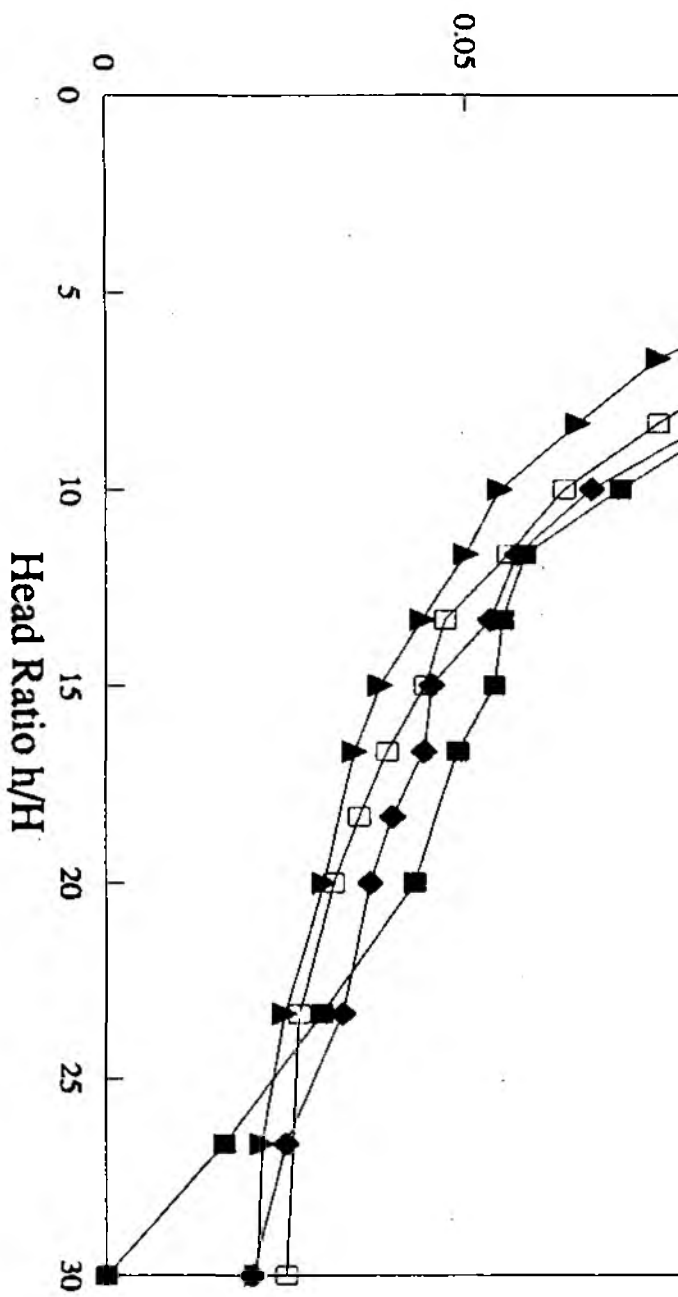
	Pump Settings			Efficiency			Power		
	Drive Pipe Dia (")	Stroke Length (mm)	Weight (g)	at 30m	at 60m	max	at 30m	at 60m	max
1)	1.5	10	507	68	83.3	88.9	16.7	17.2	18.3
2)	1.5	15	507	59.7	64.8	68.7	22.6	22.6	24.6
3)	1.5	20	507	50	54.7	60.4	24.5	25.5	28.1
4)	2	10	507	66.7	82.2	82.2	15.7	18.1	18.1
5)	2	15	507	63.2	70.8	74.2	23.5	22.6	24.5
6)	2	20	507	58	62.5	65.9	28.5	29.4	30.1
7)	2	10	730	67.1	77.8	82.6	24	24	27.5
8)	2	15	730	59.8	61.4	73.3	30.2	30.4	32.4
9)	2	20	730	51.9	58.7	61.6	33.4	36.3	36.3

GRAPH 4



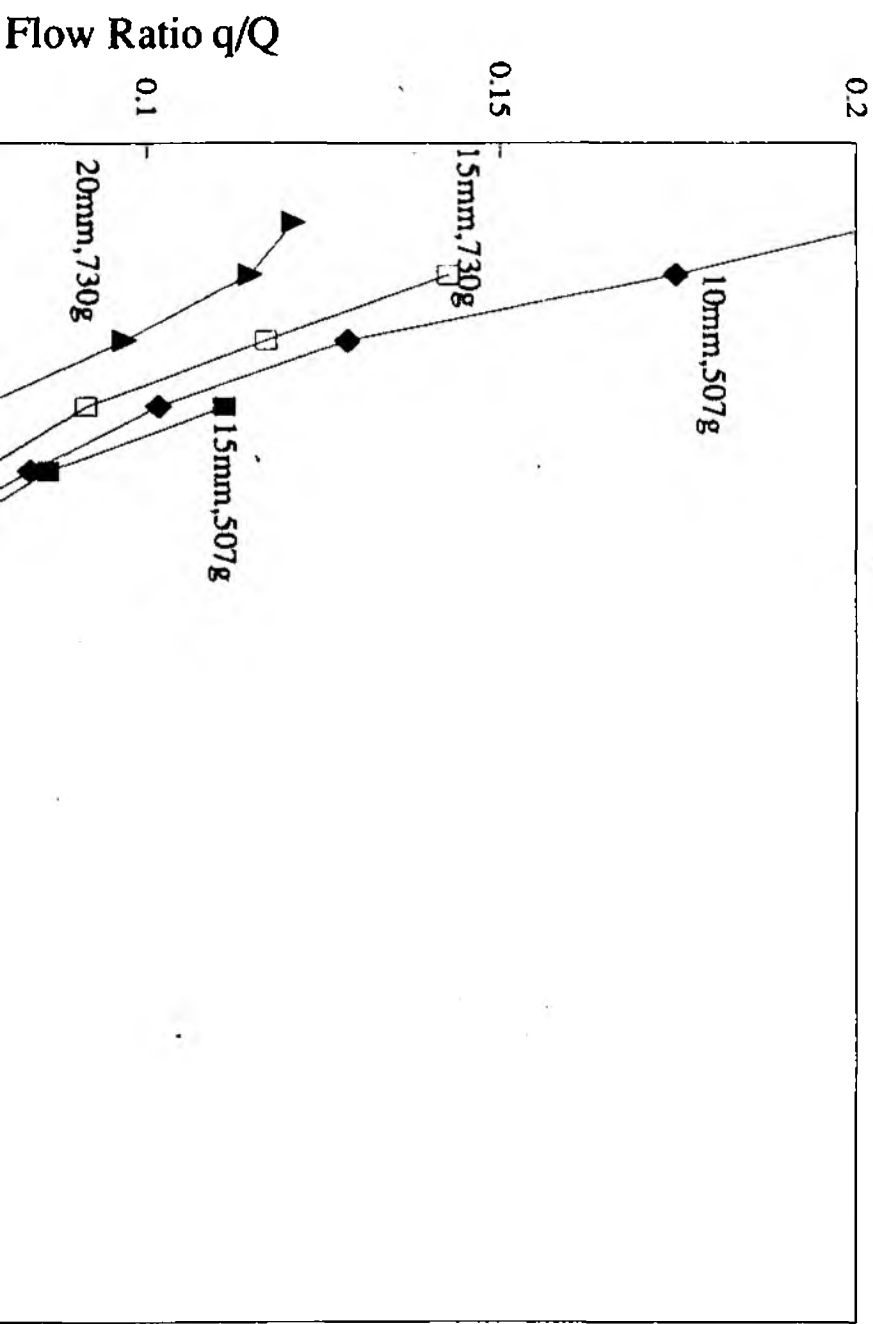
GRAPH 5





GRAPH 6

Ratio Graph for DTU M6.4



4. COMPARISON OF DTU AND COMMERCIAL PUMPS

4.1 Problems in comparison

There are inevitably problems and potential inaccuracies in taking data from two separate sets of tests carried out on two different test rigs. The main areas of difficulty are outlined below along with some explanation of their significance and potential methods for overcoming them.

- a) The drive pipe lengths of the two test rigs differ by 1.5 m with the Delft rig using an inclined pipe whereas the Warwick tests use a horizontal one. The length of the drive pipe of a hydraulic ram pump system affects (among other things) the time taken for pressure waves to traverse the length of the pipe, total friction in the system and the energy available for pumping. The exact effects of these parameters on pump performance are complicated to evaluate and given the relatively small difference can be assumed to have no major effect for the purposes of this comparison.
- b) As has already been mentioned, the Delft work is unclear about the tuning of each of the pumps tested, other than the fact that they were left constant throughout testing once installed. To allow a sensible comparison it has been assumed that the commercial pumps tested by Delft were each set to some recommended point that gave a reasonable efficiency and power output across a broad range of conditions. In order to compare the DTU pump a best average setting from those taken has been chosen and also comparisons of the optimum settings for efficiency and power. The setting chosen for the general comparison is labelled as No. 5 in Table 5 using a standard 2" drive pipe, a valve stroke of 15 mm and weight of 507 g.

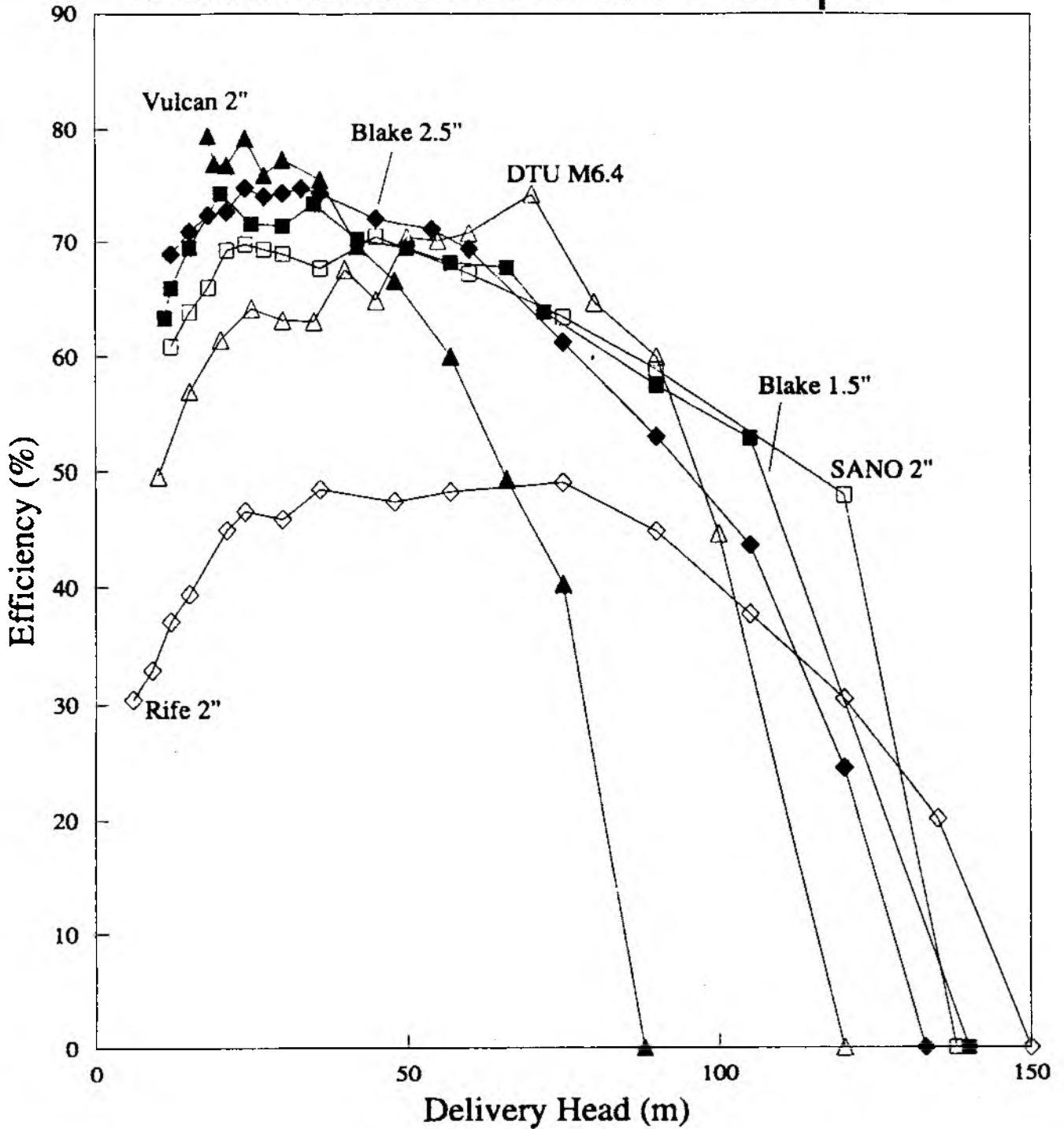
4.2 Efficiency comparisons

The efficiency of the DTU pump is of the same order as the better of the commercial models. Graph 7 shows the chosen average and peak efficiency settings of M6.4 against the 5 commercial pumps.

In a typical operating range say 20-80 m the DTU average setting gives efficiencies ranging between approx 63% and 74%. The DTU peak setting of those chosen returns results for the same range between 64% and 83%. Detailing the comparison between these settings and those for the commercial models is best done visually. The main points that can be drawn are:

GRAPH 7

Efficiency Comparison of Commercial & M6.4 Pumps



- a) The Blakes machines have the best efficiency over the widest range of delivery heads with between 62% and 75% in the 20-80 m operating band. This is very similar the DTU average setting although the shape of the curves is somewhat different giving maximum and minimum efficiencies at different heads.
- b) The DTU M6.4 pump has a markedly different efficiency profile from all the commercial models with peak efficiency occurring at much higher heads.
- c) The DTU M6.4 is capable of operating over a range of delivery heads as great as any of the commercial models.

Separate tests to determine the peak efficiency of the M6.4 have shown that it is capable of running at efficiencies of over 90%.

4.3 Power Comparison

Graph 8 shows the chosen average and peak power settings for the M6.4 against the 5 commercial pumps.

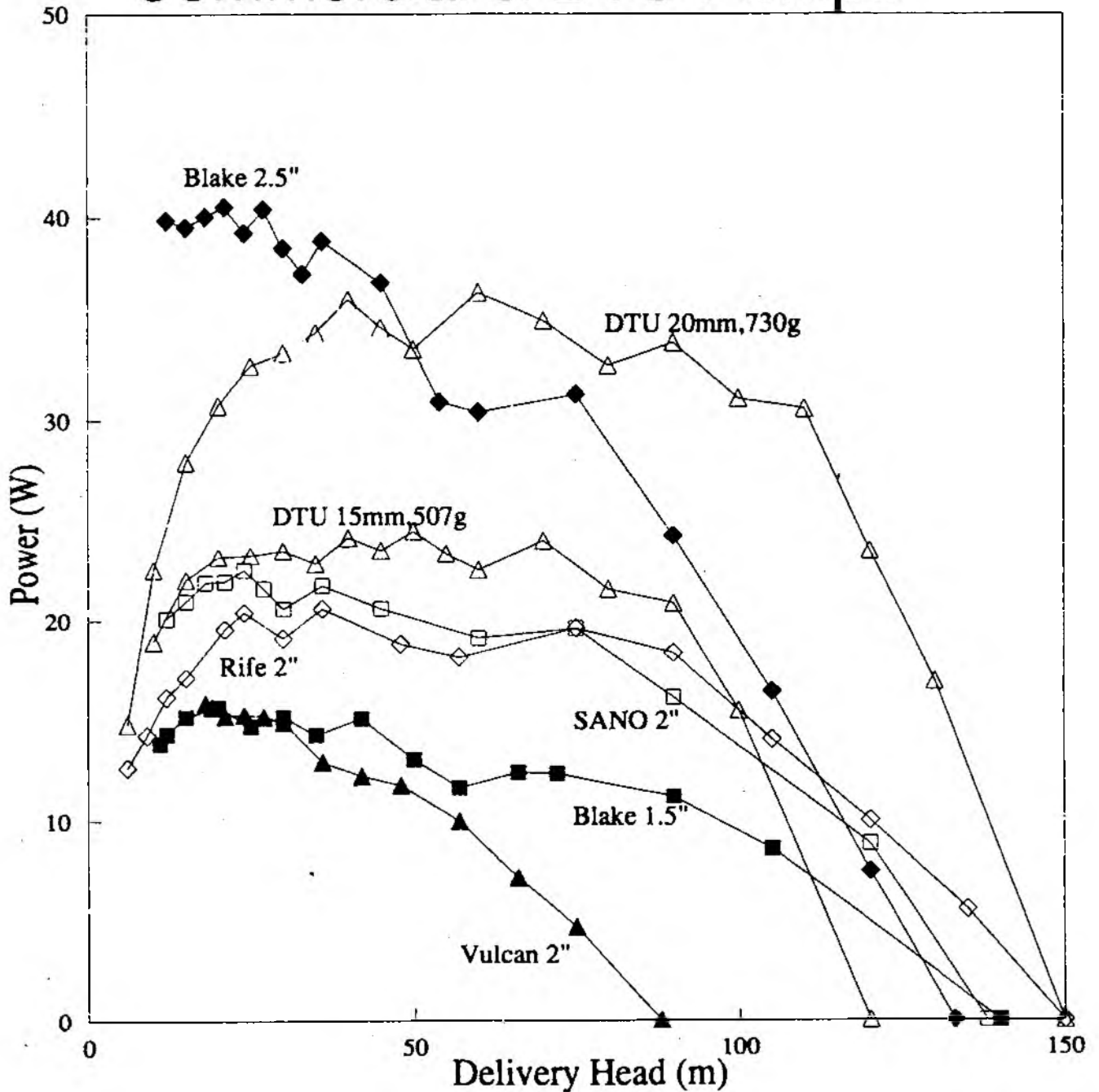
- a) The average setting of the DTU M6.4 is clearly more powerful over a very wide range of delivery heads than all of the commercial models of the same size. The Blake 2½" model is clearly more powerful as should be expected from this considerably larger capacity pump.
- b) The peak setting of the M6.4 used gives power output similar to and, at higher heads, better than even the Blake 2½" model. Increased weight on the M6.4 would further increase the power output although the limitation of the pipe size and drive head would probably limit peak power to around 40 watts.

5. COST COMPARISON

Table 2 in section 2.1 shows the costs of 10 rams in US\$ in 1982 as given by Delft. These costs are for the pumps alone with no drive pipe, delivery pipe, shipping etc. included, and range from US\$ 1000 to 3500. No updated prices are available for comparison with the DTU pump so an annual inflation rate of 5% has been assumed. A comparative cost for the DTU pumps is hard to ascertain as they have only been manufactured as one-off prototypes to date in the UK. The design of all the DTU pumps is intended to allow manufacture in the country of use, avoiding any shipping and importation problems but working to the constraints imposed in non-industrialised areas.

GRAPH 8

Power Comparison of Commercial & DTU Pumps



The Baptist Community of Western Zaire (CBZO) have a village water supply programme installing the DTU M6.4 in its rural areas. Currently the manufacture of these pumps is being contracted to a workshop in Kinshasa who are producing them in small batches as requested. The total cost of these units in Zaire is approx. US\$450 but once proper manufacture has started it is estimated that this will reduce to \$250-\$300.

The actual cost to an end user in a developing country of a ram pump will include any shipping and importation costs if it is made elsewhere. To accurately compare the DTU pumps made in country with imported commercial models the costs associated with transportation should be included. However such costs are so dependant upon the shipping distance, customs duties etc. that they would be impossible to estimate with any accuracy.

Table 6 takes the information from Table 2 and adds to the costs an allowance for inflation. It also includes information about the DTU Mark 6.4 pump for the conditions specified by Delft. The information concerning expected delivery flow was arrived at by projecting measured performance figures for different conditions. The DTU is in the process of developing a sophisticated computer simulation and model which are being used in pump analysis and will form the basis of comprehensive design charts. Ultimately this will be able to predict the performance of any pump that has been suitably calibrated under any set of conditions with a good degree of accuracy.

The predicted performance of the DTU pump ranks it 5th in terms of delivery flow and efficiency. The comparison of costs shows the vast difference in the price of the pumping unit and the cost per litre delivered. This illustrates the legitimacy of the approach of producing high performance pumps at low cost in the country of use. If a true comparison to include transportation costs were made the results would clearly be more conclusive still.

TABLE 6 - COST COMPARISON

Type of Hydraulic Ram	Pumping Rate Q [l/min]	Efficiency (Trade) (%)	Approx Price for Ram Alone [US\$-1982]	Cost per litre delivered	Rank
Vulcan 21/2	6.10	68	1800	295	4
Blake Hydram 31/2	6.00	67	1500	250	3
Sano No. 5/65 mm	6.95	77	1500	216	2
Rife 20 HDU	5.40	60	1650	306	5
Schlumpf 5A23	5.50	61	4050	737	9
Alto CH 66-110-18	5.40	60	3150	584	7
Briau D4	5.40	60	4800	890	11
CeCoCo - H50	6.90	77	5250	761	10
WAMA No. 6	4.50	50	2250	500	6
BZH-Ram W6	2.70	30	1800	666	8
DTU M6.4 2"	5.5	65	300	55	1

6. SUMMARY OF CONCLUSION

The following points summarise the conclusions that can be drawn from these tests.

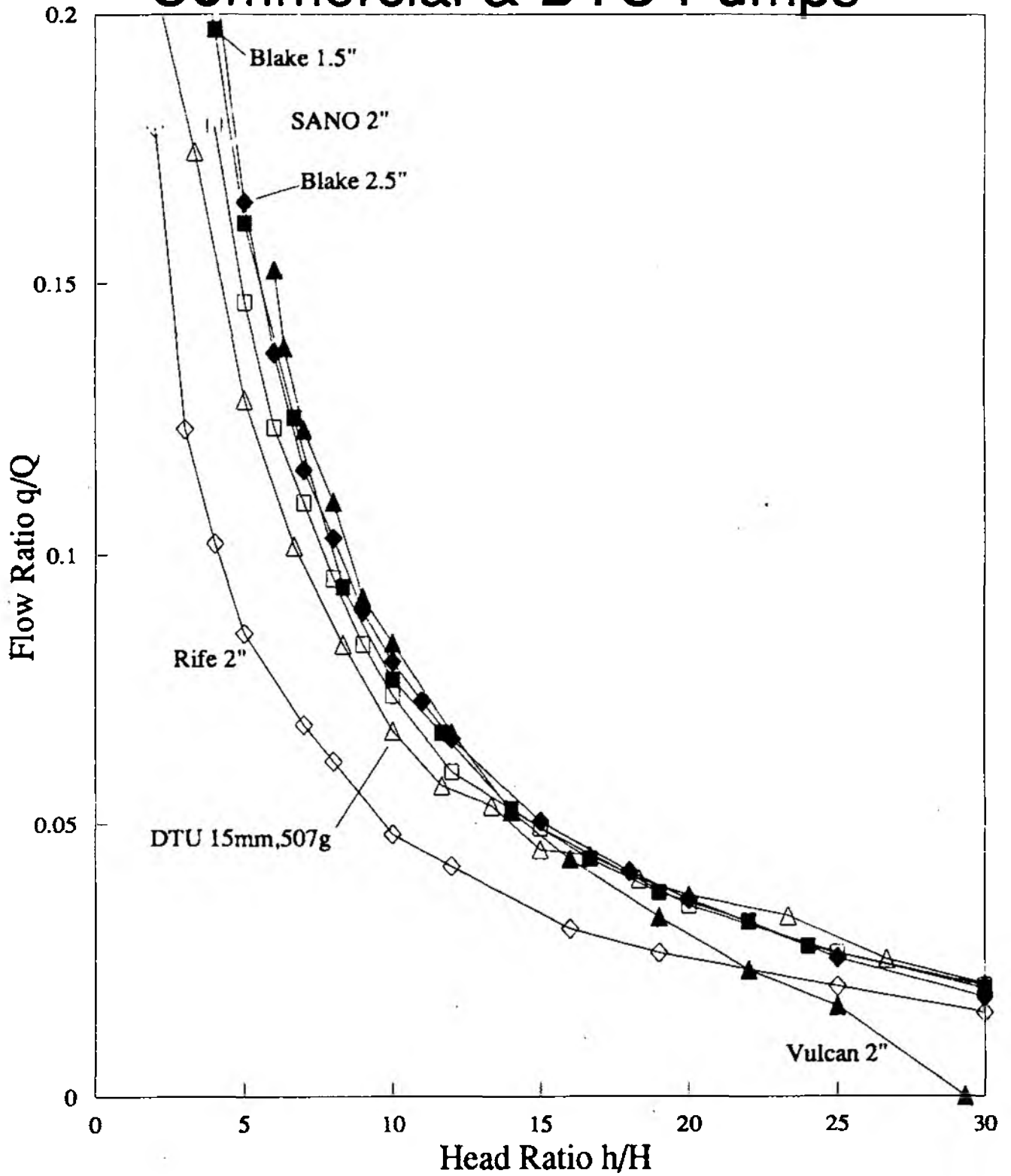
- a) The DTU Mark 6.4 pump gives efficiencies comparable with the more efficient commercial pumps over a wide range of condition.
- b) The M.6.4 produces a higher output power than all commercial models of the same size over a wide range of conditions.
- c) The M6.4 has a cost to output ratio considerably lower than all of its commercial rivals.

The tests show that it is possible to produce simple and comparatively cheap hydraulic ram pumps that can match and exceed the performance of commercial models. Whilst endurance tests to date indicate that the DTU pumps are likely to exhibit adequate durability no data is yet available for a long term comparison with commercial rivals. The current design specification is to produce low maintenance pumps whose steel components have a 10 year life and rubber components last approximately 6 months.

More detailed information concerning the design, manufacture, installation and performance of DTU pumps is available on request.

GRAPH 9

Ratio Comparison of Commercial & DTU Pumps



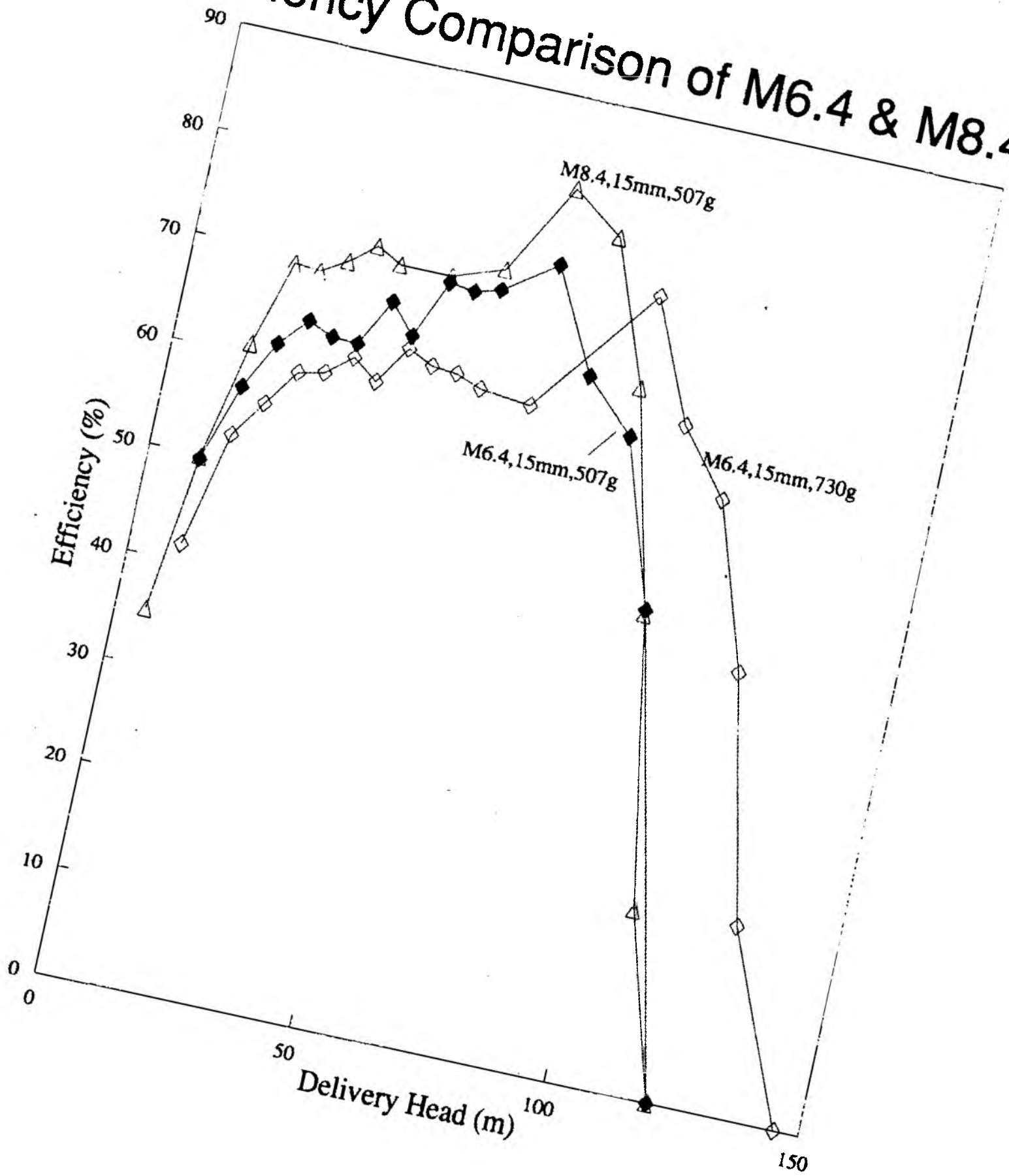
Appendix A CONTINUING DTU PUMP DEVELOPMENT

The Mark 6.4 pump was set as a DTU standard in 1990 to allow organisations interested in using the pummp to have a standard model to work with. Since that time a number of developments have occurred in the on-going research programme and new design initiatives produced. One such is the development of the Mark 8.4 that uses the same valves as the M6.4 but replaces the 2" fittings used in the pump body with a body of 4" velded construction. This alteration dramatically reduces the peak overpressure experienced the system, damps out the high frequency oscillations experienced during the cycle and increases both the efficiency and power output for any given set of conditions.

Graphs 10 and 11 allow comparison of the M8.4 with the M6.4 under identical conditions.

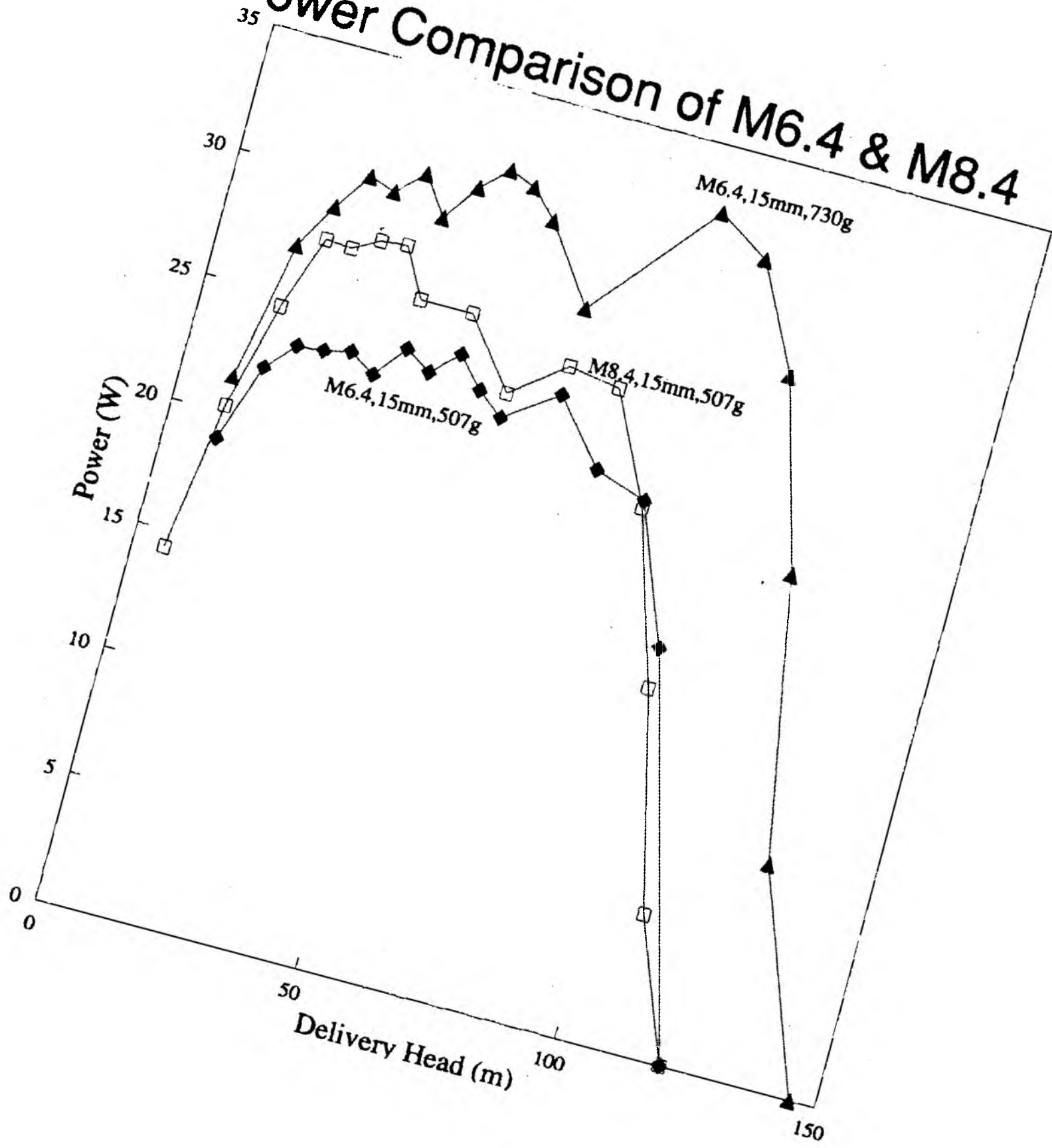
GRAPH 10

Efficiency Comparison of M6.4 & M8.4



GRAPH 11

Power Comparison of M6.4 & M8.4



Appendix B TABLES OF PERFORMANCE RESULTS

Tabulated results used in production of Graphs.

The following pages list the information supplied by Delft and that gained under similar conditions on the DTU pump. In all cases the Supply Head = 3m.

1) Blake Hydrum No2 Drive pipe dia = 1.5" Supply Head = 3.00m

Delivery Head hd	Head Ratio	Period Time	Delivery Flow	Supply Flow	Flow Ratio	Rankine Eff	D'Aub Eff	Power
11	3.666667	0.686	7.7	36.9	0.208672	55.64589	63.30344	13.84845
12	4	0.686	7.3	37	0.197297	59.18919	65.91422	14.3226
15	5	0.663	6.2	38.45	0.161248	64.49935	69.42889	15.2055
20	6.666667	0.667	4.8	38.3	0.125326	71.01828	74.24594	15.696
25	8.333333	0.669	3.6	38.3	0.093995	68.9295	71.59905	14.715
30	10	0.645	3.1	40.3	0.076923	69.23077	71.42857	15.2055
35	11.66667	0.683	2.5	37.25	0.067114	71.58837	73.37526	14.30625
42	14	0.64	2.2	41.65	0.052821	68.66747	70.23945	15.1074
50	16.66667	0.696	1.6	36.8	0.043478	68.11594	69.44444	13.08
57	19	0.737	1.25	33.6	0.037202	66.96429	68.14921	11.64938
66	22	0.714	1.15	36.2	0.031768	66.71271	67.73762	12.40965
72	24	0.695	1.05	38.4	0.027344	62.89062	63.87833	12.3606
90	30	0.697	0.76	38.9	0.019537	56.6581	57.48865	11.1834
105	35	0.758	0.5	32.6	0.015337	52.14724	52.87009	8.58375
140	46.66667		0		0	0	0	0

2) Blake Hydrum No 3.5 Drive pipe dia = 2.5" Supply Head = 3.00m

Delivery Head hd	Head Ratio	Period Time	Delivery Flow	Supply Flow	Flow Ratio	Rankine Eff	D'Aub Eff	Power
12	4	0.671	20.3	97.6	0.207992	62.39754	68.87193	39.8286
15	5	0.664	16.1	97.5	0.165128	66.05128	70.86268	39.48525
18	6	0.657	13.6	99.2	0.137097	68.54839	72.34043	40.0248
21	7	0.646	11.8	101.9	0.1158	69.47988	72.64732	40.5153
24	8	0.667	10	97	0.103093	72.16495	74.76636	39.24
27	9	0.633	9.15	102.1	0.089618	71.69442	74.02247	40.39268
30	10	0.664	7.85	97.8	0.080266	72.23926	74.30194	38.50425
33	11	0.686	6.9	94.6	0.072939	72.93869	74.77833	37.22895
36	12	0.652	6.6	100	0.066	72.6	74.29644	38.8476
45	15	0.672	5	99.1	0.050454	70.63572	72.04611	36.7875
54	18	0.735	3.5	85.1	0.041128	69.91774	71.10609	30.9015
60	20	0.727	3.1	86.3	0.035921	68.25029	69.35123	30.411
75	25	0.644	2.55	101.5	0.025123	60.29557	61.26862	31.26938
90	30	0.697	1.65	91.7	0.017993	52.18103	53.02625	24.27975
105	35	0.761	0.96	76.1	0.012615	42.89093	43.60239	16.4808
120	40	0.828	0.38	61.7	0.006159	24.01945	24.48454	7.4556
133	44.33333	0.88	0	50.3	0	0	0	0

3) Vulcan 2" Drive pipe dia = 2" Supply Head = 3.00m

Delivery Head hd	Head Ratio	Period Time	Delivery Flow	Supply Flow	Flow Ratio	Rankine Eff	D'Aub Eff	Power	
18		6	0.422	5.4	35.4	0.152542	76.27119	79.41176	15.8922
19	6.333333		0.41	5.05	36.55	0.138167	73.68901	76.88301	15.68783
21		7	0.425	4.44	36.05	0.123162	73.89736	76.75969	15.24474
24		8	0.428	3.9	35.5	0.109859	76.90141	79.18782	15.3036
27		9	0.413	3.45	37.45	0.092123	73.69826	75.91687	15.23003
30		10	0.42	3.05	36.4	0.083791	75.41209	77.31305	14.96025
36		12	0.455	2.2	32.75	0.067176	73.89313	75.53648	12.9492
42		14	0.445	1.78	34	0.052353	68.05882	69.64785	12.22326
48		16	0.44	1.5	34.55	0.043415	65.12301	66.5742	11.772
57		19	0.453	1.07	32.8	0.032622	58.71951	60.02362	9.971865
66		22	0.481	0.66	28.8	0.022917	48.125	49.28717	7.12206
75		25	0.522	0.38	23.2	0.016379	39.31034	40.28838	4.65975
88	29.33333		0	0	0	0	0	0	0

4) SANO No4 2" Drive pipe dia = 2" Supply Head = 3.00m

Delivery Head hd	Head Ratio	Period Time	Delivery Flow	Supply Flow	Flow Ratio	Rankine Eff	D'Aub Eff	Power	
12		4	0.656	10.25	57.1	0.17951	53.85289	60.87602	20.1105
15		5	0.645	8.55	58.4	0.146404	58.56164	63.85362	20.96888
18		6	0.622	7.45	60.3	0.123549	61.77446	65.97786	21.92535
21		7	0.641	6.4	58.3	0.109777	65.86621	69.24266	21.9744
24		8	0.618	5.75	60.15	0.095594	66.91604	69.80273	22.563
27		9	0.633	4.9	58.7	0.083475	66.78024	69.33962	21.63105
30		10	0.648	4.2	56.7	0.074074	66.66667	68.96552	20.601
36		12	0.608	3.7	61.9	0.059774	65.75121	67.68293	21.7782
45		15	0.653	2.8	56.8	0.049296	69.01408	70.4698	20.601
60		20	0.663	1.95	56.1	0.034759	66.04278	67.18346	19.1295
75		25	0.613	1.6	61.45	0.026037	62.48983	63.44171	19.62
90		30	0.665	1.1	54.95	0.020018	58.05278	58.876	16.1865
120		40	0.798	0.45	37.1	0.012129	47.30458	47.93609	8.829
138		46		0		0	0	0	0

5) Rife 20H DU 2" Drive pipe dia = 2" Supply Head = 3.00m

Delivery Head hd	Head Ratio	Period Time	Delivery Flow	Supply Flow	Flow Ratio	Rankine Eff	D'Aub Eff	Power	
6		2	0.965	12.9	72	0.179167	17.91667	30.38869	12.6549
9		3	0.882	9.7	78.7	0.123253	24.65057	32.91855	14.27355
12		4	0.865	8.25	80.8	0.102104	30.63119	37.05783	16.1865
15		5	0.853	7	81.85	0.085522	34.20892	39.39223	17.1675
21		7	0.847	5.7	83.1	0.068592	41.15523	44.93243	19.57095
24		8	0.828	5.2	84.2	0.061758	43.2304	46.53244	20.4048
30		10	0.858	3.9	81.1	0.048089	43.2799	45.88235	19.1295
36		12	0.835	3.5	83.25	0.042042	46.24625	48.41499	20.601
48		16	0.866	2.4	78.7	0.030496	45.74333	47.34895	18.8352
57		19	0.89	1.95	74.9	0.026035	46.86248	48.2108	18.17303
75		25	0.858	1.6	80	0.02	48	49.01961	19.62
90		30	0.84	1.25	82.4	0.01517	43.99272	44.82965	18.39375
105		35	0.888	0.82	75.3	0.01089	37.02523	37.70363	14.07735
120		40	0.947	0.51	66.5	0.007669	29.90977	30.44322	10.0062
135		45	0.999	0.25	55.75	0.004484	19.73094	20.08929	5.518125
154	51.33333			0		0	0	0	0

6) DTU M6.4 2" 1.5" Drive pipe Stroke = 10mm

Weight 507g

Delivery Head hd	Head Ratio	Period Time	Delivery Flow	Supply Flow	Flow Ratio	Rankine Eff	D'Aub Eff	Power
8	2.666667	0.965	10	52	0.238095	39.68254	43.01075	13.08
12	4		8.1	51	0.188811	56.64336	54.82234	15.8922
15	5		6.8	52	0.150442	60.17699	57.82313	16.677
20	6.666667		5.2	51	0.113537	64.3377	61.68446	17.004
25	8.333333		4.2	52	0.087866	64.43515	62.27758	17.1675
30	10		3.4	50	0.072961	65.66524	63.67041	16.677
35	11.66667		3	51	0.0625	66.66667	64.81481	17.1675
40	13.33333		2.4	48	0.052632	64.91228	63.49206	15.696
45	15		2.2	48	0.048035	67.24891	65.73705	16.1865
50	16.66667		2.1	47	0.046771	73.27394	71.2831	17.1675
56	18.66667		2	42	0.05	88.33333	84.84848	18.312
60	20		1.75	42	0.043478	82.6087	80	17.1675
70	23.33333		1.2	42	0.029412	65.68627	64.81481	13.734
80	26.66667		0.6	41	0.014851	38.11881	38.46154	7.848
90	30		0	40	0	0	0	0

7) DTU M6.4 2" Drive pipe 1.5" Stroke 15mm

Weight 507g

Delivery Head hd	Head Ratio	Period Time	Delivery Flow	Supply Flow	Flow Ratio	Rankine Eff	D'Aub Eff	Power
7	2.333333	0.965	14.5	77	0.232	30.93333	36.97632	16.59525
10	3.333333		11.7	79	0.173848	40.56464	42.9989	19.1295
15	5		9	79	0.128571	51.42857	51.13636	22.0725
20	6.666667		7	78	0.098592	55.86854	54.90196	22.89
25	8.333333		5.5	78	0.075862	55.63218	54.89022	22.48125
30	10		4.6	77	0.063536	57.18232	56.37255	22.563
35	11.66667		4.05	77	0.055517	59.21864	58.29735	23.17613
40	13.33333		3.4	74	0.048159	59.39566	58.5702	22.236
45	15		3.1	76	0.042524	59.53361	58.78635	22.80825
50	16.66667		2.8	74	0.039326	61.61049	60.76389	22.89
55	18.33333		2.5	71	0.036496	63.26034	62.35828	22.48125
60	20		2.3	71	0.033479	63.6099	62.7558	22.563
70	23.33333		2.15	73	0.030346	67.77229	66.75538	24.60675
80	26.66667		1.75	68	0.026415	67.79874	66.90562	22.89
90	30		1.35	62	0.022259	64.5507	63.93054	19.86525
100	33.33333		1.15	61	0.019215	62.12754	61.67873	18.8025
110	36.66667		0.7	60	0.011804	42.1023	42.28446	12.5895
120	40		0	58	0	0	0	0

8) DTU M6.4 2" Drive pipe 1.5" Stroke 20mm

Weight 507g

Delivery Head hd	Head Ratio	Period Time	Delivery Flow	Supply Flow	Flow Ratio	Rankine Eff	D'Aub Eff	Power
6	2	0.965	13.5	101	0.154288	15.42857	23.58079	13.2435
10	3.333333		11.8	100	0.133787	31.21693	35.18187	19.293
15	5		9.4	100	0.103753	41.5011	42.96161	23.0535
20	6.666667		7.2	100	0.077586	43.96552	44.77612	23.544
25	8.333333		6	100	0.06383	46.80851	47.16981	24.525
30	10		4.9	98	0.052632	47.36842	47.61905	24.0345
35	11.66667		4.2	98	0.044776	47.78119	47.94521	24.0345
40	13.33333		3.9	100	0.040583	50.05203	50.04812	25.506
45	15		3.5	98	0.037037	51.85185	51.72414	25.75125
50	16.66667		3.25	97	0.034667	54.31111	54.03159	26.56875
55	18.33333		2.9	96	0.031149	53.99212	53.758	26.07825
60	20		2.6	95	0.028139	53.4632	53.27869	25.506
70	23.33333		2.3	94	0.025082	56.01599	55.72863	26.3235
80	26.66667		2.15	95	0.023156	59.43278	59.01527	28.122
90	30		1.7	93	0.01862	53.99781	53.85428	25.0155
100	33.33333		1.3	90	0.014656	47.3882	47.46258	21.255
125	41.66667		0	0	0	0	0	0

9) DTU M6.4 2" Drive pipe 2" Stroke 20mm

Weight 507g

Delivery Head hd	Head Ratio	Period Time	Delivery Flow	Supply Flow	Flow Ratio	Rankine Eff	D'Aub Eff	Power
7	2.333333	0.965	14	108	0.148936	19.85816	26.77596	16.023
10	3.333333		13.3	108	0.140444	32.77015	36.5485	21.7455
15	5		11.3	106	0.119324	47.72967	48.16709	27.71325
20	6.666667		8.7	105	0.090343	51.19418	51.01143	28.449
25	8.333333		7.1	103	0.074035	54.29267	53.73903	29.02125
30	10		5.8	100	0.061571	55.41401	54.82042	28.449
35	11.666667		5.2	102	0.053719	57.30028	56.59204	29.757
40	13.333333		4.4	100	0.046025	56.7643	56.19413	28.776
45	15		3.9	98	0.041445	58.02338	57.40922	28.69425
50	16.666667		3.5	97	0.037433	58.64528	58.04312	28.6125
55	18.333333		3.35	96	0.036158	62.67314	61.81849	30.12488
60	20		3	96	0.032258	61.29032	60.60606	29.43
70	23.333333		2.3	89	0.026528	59.24644	58.78058	26.3235
80	26.666667		2.1	85	0.025332	65.01809	64.29392	27.468
90	30		1.6	86	0.018957	54.9763	54.79452	23.544
100	33.333333		1.3	86	0.015348	49.62613	49.63727	21.255
110	36.666667		0.85	84	0.010222	36.46021	36.73149	15.28725
130	43.333333		0			ERR	ERR	0

10) DTU M6.4 2" Drive pipe 2" Stroke 15mm

Weight 507g

Delivery Head hd	Head Ratio	Period Time	Delivery Flow	Supply Flow	Flow Ratio	Rankine Eff	D'Aub Eff	Power
6	2	0.965	13.3	78	0.205564	20.55641	29.13472	13.0473
10	3.333333		11.6	78	0.174699	40.76305	43.15476	18.966
15	5		9	79	0.128571	51.42857	51.13636	22.0725
20	6.666667		7.1	77	0.101574	57.55842	56.2822	23.217
25	8.333333		5.7	74	0.083455	61.20059	59.59849	23.29875
30	10		4.8	76	0.067416	60.67416	59.40594	23.544
35	11.666667		4	74	0.057143	60.95238	59.82906	22.89
40	13.333333		3.7	73	0.053391	65.84897	64.31986	24.198
45	15		3.2	74	0.045198	63.27684	62.17617	23.544
50	16.666667		3	71	0.044118	69.11765	67.56757	24.525
55	18.333333		2.6	68	0.039755	68.90928	67.51653	23.3805
60	20		2.3	65	0.036683	69.69697	68.35087	22.563
70	23.333333		2.1	66	0.032864	73.39593	71.95301	24.0345
80	26.666667		1.65	68	0.024868	63.82818	63.17301	21.582
90	30		1.42	71	0.020408	59.18367	58.82353	20.8953
100	33.333333		0.95	71	0.013562	43.84963	44.01205	15.5325
120	40							

11) DTU M6.4 2" Drive pipe 2" Stroke 10mm

Weight = 507g

Delivery Head hd	Head Ratio	Period Time	Delivery Flow	Supply Flow	Flow Ratio	Rankine Eff	D'Aub Eff	Power
20	6.666667	0.965	4.8	48	0.111111	62.96296	66.66667	15.696
25	8.333333		3.8	48	0.085973	63.04676	65.97222	15.5325
30	10		3.2	48	0.071429	64.28571	66.66667	15.696
35	11.666667		2.7	49	0.058315	62.20302	64.28571	15.45075
40	13.333333		2.35	45	0.0551	67.95623	69.62963	15.369
45	15		2.15	42	0.053952	75.53325	76.78571	15.81863
50	16.666667		2	43	0.04878	76.42276	77.51938	16.35
60	20		1.85	45	0.042874	81.46002	82.22222	18.1485
70	23.333333		1.25	43	0.02994	66.86627	67.82946	14.30625
80	26.666667		0.6	37	0.016484	42.30769	43.24324	7.848
90	30		0	0	0	0	0	0

12) DTU M6.4 2" Drive pipe 2" Stroke 10mm Weight 730g

Delivery Head hd	Head Ratio	Period Time	Delivery Flow	Supply Flow	Flow Ratio	Rankine Eff	D'Aub Eff	Power
20	6.666667	0.965	7.3	77	0.104735	59.34959	63.20346	23.871
25	8.333333		5.9	75	0.085384	62.61457	65.55556	24.11625
30	10		4.9	73	0.071953	64.75771	67.12329	24.0345
35	11.66667		4.1	71	0.061286	65.3712	67.37089	23.46225
40	13.33333		3.9	77	0.053352	65.80027	67.53247	25.506
45	15		3.6	73	0.051873	72.62248	73.9726	26.487
50	16.66667		2.8	67	0.043614	68.32814	69.65174	22.89
60	20		2.45	63	0.040462	76.87861	77.77778	24.0345
70	23.33333		2.3	65	0.038883	81.92451	82.5641	26.3235
80	26.66667		2.1	71	0.030479	78.22932	78.87324	27.468
90	30		1.63	71	0.023497	68.14185	68.87324	23.98545
100	33.33333		1.15	62	0.018899	61.10655	61.82796	18.8025
110	36.66667		0.5	60	0.008403	29.97199	30.55556	8.9925
120	40		0	60	0	0	0	0

13) DTU M6.4 2" Drive pipe 2" Stroke 15mm Weight 730g

Delivery Head hd	Head Ratio	Period Time	Delivery Flow	Supply Flow	Flow Ratio	Rankine Eff	D'Aub Eff	Power
10	3.333333	0.965	13.1	105	0.142546	33.26079	41.5873	21.4185
15	5		11	105	0.117021	48.80851	52.38085	26.9775
20	6.666667		8.8	105	0.091476	51.83645	55.87302	28.776
25	8.333333		7.4	104	0.076605	56.17667	59.29487	30.2475
30	10		6.1	102	0.063608	57.24713	59.80392	29.9205
35	11.66667		5.4	102	0.055901	59.62733	61.78471	30.9015
40	13.33333		4.5	100	0.04712	58.11518	60	29.43
45	15		4.2	99	0.044304	62.02532	63.63636	30.9015
50	16.66667		3.9	104	0.038961	61.03896	62.5	31.8825
55	18.33333		3.5	103	0.035176	60.97152	62.29773	31.47375
60	20		3.1	101	0.031665	60.16343	61.38614	30.411
70	23.33333		2.4	92	0.026786	59.82143	60.86957	27.468
90	30		2.2	90	0.025057	72.66515	73.33333	32.373
100	33.33333		1.9	102	0.018981	61.37196	62.0915	31.065
110	36.66667		1.5	98	0.015544	55.44041	56.12245	26.9775
120	40		1	98	0.010309	40.20819	40.81633	19.62
130	43.33333		0.4	98	0.004098	17.34973	17.68707	8.502
145	48.33333		0	98	0	0	0	0

14) DTU M8.4 2" Drive pipe 2" Stroke 20mm Weight 730g

Delivery Head hd	Head Ratio	Period Time	Delivery Flow	Supply Flow	Flow Ratio	Rankine Eff	D'Aub Eff	Power
6	2	0.965	15.1	140	0.120897	12.08967	21.57143	14.8131
10	3.333333		13.8	134	0.114809	26.78869	34.32836	22.563
15	5		11.4	129	0.096939	38.77551	44.18605	27.9585
20	6.666667		9.4	132	0.076672	43.44753	47.47475	30.738
25	8.333333		8	130	0.065574	48.08743	51.28205	32.7
30	10		6.8	131	0.05475	49.27536	51.9084	33.354
35	11.66667		6	126	0.05	53.33333	55.55556	34.335
40	13.33333		5.5	131	0.043825	54.05046	55.97984	35.97
45	15		4.7	128	0.038118	53.36577	55.07813	34.58025
50	16.66667		4.1	123	0.034483	54.02299	55.55556	33.5175
60	20		3.7	126	0.030253	57.4816	58.73016	36.297
70	23.33333		3.05	126	0.024807	55.40192	56.48148	34.90725
80	26.66667		2.5	118	0.021645	55.55556	58.49718	32.7
90	30		2.3	112	0.020966	60.80219	61.60714	33.8445
100	33.33333		1.9	112	0.017257	55.79776	56.54762	31.065
110	36.66667		1.7	117	0.014744	52.58745	53.27635	30.5745
120	40		1.2	119	0.010187	39.72835	40.33613	23.544
130	43.33333		0.8	118	0.006826	28.89647	29.37853	17.004
150	50		0	116	0	0	0	0

Appendix C FURTHER NOTES AND COMMENTS ON THE WORK AT DELFT

The following are a series of points arising from the work at Delft that have not been mentioned in the main text of this paper.

- 1) Delft managed to record delivery valve movement of rubber type valves by bonding strain gauges to the rubber. This technique overcomes the difficulty of recording and analysing delivery valve movement experienced by the DTU.
- 2) An electronic beat frequency counter was used at Delft to record the operating frequency and period of pumps under test. This is another technique worth pursuing for ongoing tests at Warwick.
- 3) There is some confusion and lack of consistency between ram pump manufacturers and users as to how efficiency is measured. Delft produce the following summary

Rankine Drive tank water level is taken as the datum point and supply and delivery heads measured from that point. Therefore the net amount of potential energy in the water delivered = $pgq(h \cdot H)$
the net amount of energy input = $pgQH$

$$\text{Hence Rankine efficiency } \eta_R = \frac{q \times (h-H)}{Q \times H}$$

D'Aubuisson The impulse valve orifice is taken as the datum point and therefore

$$\begin{aligned} \text{work done} &= pgqh \\ \text{energy supply} &= pg(Q + q)H \\ \text{D'Aubuisson Efficiency } \eta_D &= \frac{q \times h}{(Q + q) \times H} \end{aligned}$$

Manufacturers

Most manufacturers take a simplified efficiency that actually produces a higher value of efficiency under any given set of conditions

$$\eta_m = \frac{q \times h}{Q \times H}$$

Delft prefer the Rankine expression which yields the lowest results particularly at low

delivery heads.

The DTU currently uses the D'Aubuisson formula as the test rig measures the total flow into the pump ($Q + q$) rather than just the waste flow. This has been used throughout this report.

There seems little to choose between these two which produce similar results under normal operating conditions. The simplified efficiency used by many manufacturers is more inaccurate but produces more flattering figures!

- 4) Observation on relative position of delivery and impulse valves concerning air intake during recoil.

During recoil, large quantities of air can be drawn in through the open impulse valve as water flows back up the drive pipe. Only a small quantity of air can be drawn through the snifter valve so section A remains relatively full of water. As acceleration of water towards the pump re-occurs the majority of the air is expelled through the impulse valve and only the small volume entering from the snifter enters the air vessel.

If the recoil is large in this configuration and a significant quantity of air drawn in through the impulse valve, the column may recede past the vertical pipe section leading to the delivery valve. When acceleration occurs a significant pocket of air may be trapped under the delivery valve. This would tend to dampen out the next pressure pulse and reduce delivery flow.

- 5) The Alto ram from France has an inflatable rubber air compartment in the air vessel to ensure a permanent separation of air and water. This is an attractive option as it reduces the need for a reliable snifter to replenish air lost from the air vessel.
- 6) The SANO rams are fitted with a 'drip valve' in the air vessel that appears to be located at a point where the air/water interface should be. It presumably operates by passing water if the level in the air vessel rises above it. What is its operating mechanism?
- 8) Delft draw the following conclusions about pump performance and operation from results produced by their mathematical model.

- given an available source supply the pumping rate (q) is primarily determined by the supply head (H_s) and the delivery head (h_d).
 - an increase of the delivery head (h_d) decreases the quantity pumped per cycle (V_d) and by that the pumping rate (q) decreases.
 - an increase of the supply head (H_s) increases the pumping frequency and by that the pumping rate (q) increases.
 - an increase of u_c (ie. the velocity of the water in the drive pipe at waste valve closure) normally increases the pumping rate (q) while the pumping frequency decreases, but more water (Q) is needed to operate the ram. However, there is a limitation as to this point: an increase in u_c such that the value of the ratio u_c/u_0 approaches unity (where u_0 is the maximum attainable velocity of the water in the drive pipe) implies a decrease in pumping rate (q) while, as before, the waste flow (Q) increases, a condition to be avoided.
 - the larger the size (ie. drive pipe bore) of the ram, the more water (Q) is required to operate the ram and the more water (q) can be delivered to a higher level (h_d).
- 9) Delft recommend that if the delivery flow from one ramains insufficient a second ram should be placed below the first and utilise its drive water. However if there is sufficient drive head available to be able to do this would a better performance be gained by having two rams each working from a portion of the drive head or one ram working with the total head available?
- 10) Delft state that the drive pipe length should be approximately 4 to 7 times the supply head. They make no justification for this statement.
- 11) Delft state that the best pumping results are usually obtained when the cut off velocity is between 60% and 80% of the terminal velocity of the system.
- 12) Delft produce equations for predicting pump performance, which require certain information about the system to be known.

A loss coefficient for the whole system is required which covers all the losses in the drive pipe, pump and delivery pipe. Delft state that this can be found by holding open the impulse valve, measuring the flow rate at terminal velocity and inserting this into the equation

$$\text{max velocity } V = \sqrt{\frac{2gH}{\text{loss coef}}}$$

This does not take into account the delivery system losses and can only be measured

once the system is installed, preventing prediction of performance prior to installation. It would be more useful to have a loss coefficient measured for each pump and also to have a simple method of calculating pipe loss coefficient based on diameter and length.

The other requirement for use of Delft's model is to find the cut off velocity for the particular impulse valve setting. They state that this can be found when the maximum delivery head obtainable is known using

$$\text{Cutoff} = (g/c) \times h_{\text{max}}$$

They recommend that h_{max} is found by closing the delivery side of the pump and letting the pump run up to its maximum head. This would provide a rather crude approximation producing a low result and could prove to be very dangerous.