Oslo Symposium
12-82

THE COLLECTION OF OIL
FROM SUBSEA WELL BLOWOUTS

by

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Introduction

The most ambitious attempt to collect oil immediately above a subsea blowout was the installation of a collection device carried out at the IXTOC 1 blowout. Figure 1 shows a photograph of this collection device. Oil, gas and water entered the conical collector above the wellhead and was carried by gas-lift up the sloping riser to a platform to which the truss which supported the collector was clamped.

Although only a few percent of the blowout oil was collected by the IXTOC 1 collector, the concept it utilized seemed feasible and it seemed likely that considerably more oil could be collected if the collector were somewhat closer to the blowing well then was the case at IXTOC where the bottom of the collector was approximately 10 meters above the wellhead. Because of this, an experimental program on subsurface collectors was undertaken. This program included experiments both at relatively small laboratory scale and at approximately 25% of full-scale.

The Laboratory Scale Tests

The laboratory scale tests are explained in detail in reference 1. A summary is given here. The tests were carried out in a cylindrical tank whose dimensions are shown in figure 2. The collectors had the form of inverted funnels with octagonal cross-sections and were built to approximately 1/15th of the expected full-scale. A total of 5 collectors were constructed. One was a special double collector, and the remaining four were single funnel-shaped collectors having different proportions. Figure 3 shows these four collectors.

In use, the flow was driven up the riser attached to the top of the collector by gas-lift as is the case for a full-scale collector. For the tests, the flow-rate was varied by changing the riser resistance with a valve located near the top of the riser. In each experiment, gas and oil flow rates were known and the collected oil and water flows were determined by sampling the liquid coming through the riser system. The experimental arrangement which was used is sketched in figure 4.

An analysis of the data showed that when all of the blowout gas entered the collection system, the principal dimensionless parameters which influenced the fraction of blowout oil collected were the Froude number, F, and the phase ratio R, which are given by:

$$F = \frac{Q_T}{\sqrt{gh^5}} \qquad (1)$$

$$R = \frac{Q_T}{q} \qquad (2)$$

where: Q_T is the liquid volume flow rate in the system 2,

q is the gas volume flow rate,

g is the acceleration of gravity, and,

h is the distance from the wellhead to the bottom of the collector.

An interpolating function which gives the percentage of blowout oil collected in terms of the Froude number and phase ratio was constructed which matched the laboratory data to within an RMS error of 8.7%. This function is:

$$P = 100x\left[1-\exp\left(\frac{AxRxF}{B+R}\right)\right]^C \qquad (3)$$

where P is the percent of blowout oil collected and

$$A = 77.03 \qquad B = 1.419 \qquad C = 0.428 \qquad (4\ a,b,c)$$

For cases where some of the blowout gas escaped outside the collector, an increase in fraction of blowout oil was often observed to occur. This led to the conclusion that under many circumstances, a collection system could encounter more than the optimum amount of gas. To aid in overcoming the reduction in collection efficiency resulting from excess gas, a gas-separating collector, as shown in figure 5 was designed. It was originally planned that this collector would operate with most of the gas passing through the central riser with just enough gas escaping from the inner-cone to the outer-cone to drive the outer riser at maximum efficiency. To operate a gas-separating (henceforth called double) collector in this way requires adjustment of the inner riser resistance by means of a control valve to make it suit the operating conditions. Subsequent experiments in the laboratory revealed an efficient mode of operation which did not require such an adjustment. This was to fit both the inner and outer collectors with equal size risers and to collect liquid from both risers. Under conditions having a high Froude number and a high phase ratio, no gas would escape from the inner collector and only the inner riser would pump liquid. If the gas flow-rate is increased from that yielding an efficient operating condition, the continuous liquid phase interface moves lower in the inner collector. Under conditions for which the inner collector operating alone becomes inefficient, some gas escapes from the inner collector to the outer collector and this outer collector begins pumping. With both risers operating, the total collected liquid flow-rate increases which yields an increased Froude number and a higher efficiency. If the amount of gas is increased still further, the interface will move so low in the inner collector that it will choke and pass only gas while the outer collector pumps liquid as a result of the gas-lift from that gas which escapes from the inner collector. This condition, for extremely large amounts of gas is the one which was initially planned for the double collector.

To test the double collector in the above described "automatic mode", the model collector shown in figure 5 was fitted with 2 identical risers each having an inside diameter of 3.38 cm. Table 1 shows the results for the tests on the laboratory model of the double collector where Froude numbers and phase ratios are based on the sum of the flows in both risers. The table also shows the predicted collection percentage for a single collector operating at the same Froude number and phase ratio as given by equation (3). The table clearly demonstrates that under conditions where a single collector becomes inefficient, a substantial gain in efficiency is achieved by use of a double collector.

Intermediate Scale Test Apparatus and Procedures

Intermediate scale tests were conducted in Bugg Spring, which is a natural sinkhole spring having a depth of 53 meters and a mean surface diameter of 110 meters, located at Okahumpka, Florida. Complete details appear in reference 2. Figure 6 shows drawings of Bugg Spring and the position of a tightly moored barge that was used for a work platform. Figure 7 shows a diagram of the apparatus that was used for the experiments.

Previous laboratory experiments showed that the wellhead oil was broken down into small droplets having diameters much less than 1 mm which were mixed into a volume of water which was much larger than that of the oil. Under these conditions, the oil acts as a tracer for the water flow. This finding was used for the Bugg Spring experiments inasmuch as it was not feasible to pump oil into the spring. Fluroscein dye was used as a tracer and quantitative measurements of the percentage of blowout dye collected were made by means of fluorimetry.

The blowout gas was simulated by air supplied from an air compressor fitted with valves and an air bleed off arrangement so that any flow rate up to 0.71 standard cubic meters/second could be supplied to the wellhead. The collector-wellhead assembly shown in figure 8 was attached to the base of the collector. The wellhead to collector base height could be varied from 0.04 to 2.20 m by adjusting a wire rope cable on the surface which ran down the riser and was attached to the wellhead by a system of sheaves.

Three different collector configurations were tested: a single collector, a double collector and a straight riser pipe collector. The single and double collectors were built to have the same general shape as the collectors used in the laboratory experiments, but were scaled to be four times as large. The straight riser pipe collector had the same internal diameter as the risers used for the single and double collectors (20.3 cm). Laboratory scale tests had indicated that a riser alone could collect a significant percentage of blowout oil. The user of a riser without a collector offers advantages in certain field applications where a surface fire caused by escaping gas which is not collected, can be tolerated.

As shown in figure 9, the entire collector system was anchored to the bottom by three moorings. A fourth wire rope was attached to the top of the collector and ran up to the surface barge and this wire rope was tensioned to a force of about 1 ton.

For each collector test, with known values of wellhead distance, dye concentration, dye delivery rate and air delivery rate, the additional quantities to be measured were liquid collection rate and dye concentration in the collected liquid. The collection rates were measured by means of measurement of volumes collected during specific time intervals and concentrations were measured by use of a Farand Model A-4 Fluorometer. This instrument was fitted with a 490 nanometer interference filter for excitation of the sample and a Farand Model 3-69 Filter for sample emission. Figure 10 shows the flow output from an operating riser.

The double collector was tested at 13 operating conditions; the single collector at 16 conditions and the riser alone without a collector was tested at 14 operating conditions. Operating conditions and measured quantities are shown in tables 2,3 and 4.

The data interpolation function given by equation(3) is based on a phase ratio determined from the gas flow rate at a pressure of 1 atmosphere. That interpolation function is satisfactory for all of the laboratory experiments because they were all taken at the same water depth. However, for comparing the laboratory scale measurements with the intermediate scale measurements, it is necessary to consider gas flow rates at the collector entrance inasmuch as it is this quantity which influences the fluid mechanics of the collector. Henceforth, the phase ratio R will be considered on the basis of the gas flow rate at the collector, which is the gas flow rate at a pressure of 1 atmosphere multiplied by the ratio of 1 atmosphere to the absolute pressure at the collector entrance. In order to adjust equation (3) for phase ratios calculated in this way it is only necessary to modify the coefficient B to it's previous value multiplied by the ratio of absolute pressure at the bottom to that at the surface. For the laboratory experiments, this ratio is 1.33 so that the value of B of 1.41879 shown in equation 4 becomes 1.88699 for use with air flow rates at the collector entrance.

When equation (3) is applied to the intermediate scale single collector data the RMS error is found to be 10.9%. A study was made to determine why this was larger than the 8.7% found with the laboratory scale data for which the interpolating function was constructed; and to generate a new interpolating function that could be more accurately applied to all of the laboratory and intermediate scale data simultaneously. Two responsible scale-dependent phenomena were identified.

Observations of gas-bubble plumes in the laboratory showed that immediately above the well-head the plume has a rather cylindrical shape. Its generally conical form begins a small distance above the wellhead with the projected apex of the cone lying above the wellhead. It seems quite possible that the plume does not entrain much surrounding water until the bubbles emanating from the wellhead burst for the first time with this occurring some distance above the wellhead. This phenomenon can be included in the interpolating function by using a modified Froude number F' in lieu of the Froude number F where:

$$F' = \frac{Q_T}{\sqrt{g(h-D')^5}} \qquad (5)$$

The quantity D' must have the same order of magnitude as the distance between the wellhead and the height at which the bubbles burst first. For this study, D' is taken as a constant to be determined such that the interpolating function gives the best fit to all of the data.

The second scale-dependent phenomenon is the ratio between the bubble size and an appropriate overall length scale. The fundamental length scale of the buoyant flow is called L_A and is given by:

$$L_A = q_A^{0.4}/g^{0.2} \qquad (6)$$

where q_A is the gas volume flow rate at the collector entrance. The length scale of the bubbles is called L_B and is given by:

$$L_B = \sqrt{\frac{T}{\rho_w g}} \qquad (7)$$

where T is the gas-liquid surface tension (taken here as 0.072 Newtons/meter) and ρ_w is the mass density of water (taken here as 1000 Kg/meter^3). The reduction of buoyancy due to the weight of the gas has been neglected. An increase in the amount of gas (lower phase ratio) reduces oil collection efficiency. This is accounted for in the interpolating function through the effect of the phase-ratio, R. The scale-dependent effect of bubble size is included here by replacing the phase ratio R with a modified phase ratio R' given by:

$$R' = R\left(1+E'\frac{L_B}{L_A}\right) \qquad (8)$$

The dimensionless constant E' is to be determined so that the best fit between all of the data, both laboratory and intermediate scale, and the interpolating function is obtained. An appropriate new interpolating function was found to be

$$P = 100\left[1-\exp\left(\frac{-A'xR'xF'}{B'+R'}\right)\right]^{C'} \qquad (9)$$

where P is the percentage of blowout oil collected and A', B', C', D' and E' are constants. Their values were determined to minimize the RMS error between equation 9 and the single collector laboratory scale data and the Bugg Spring data together. These are:

$$\begin{aligned} A' &= 59.69 \\ B' &= 6.99 \\ C' &= 0.373 \\ D' &= 0.111 \text{ meters} \\ E' &= 11.77 \end{aligned} \qquad (10, a,b,c,d,e)$$

NOTE: In use of equation (9), when h<D', P is to be set to 100%.

The standard deviation over all of the data points between the interpolating function and the measurements is 8.2% which is an improvement over the 8.7% for the application of equation (3) to the laboratory data only. A set of smooth curves of percentage of blowout oil collected versus modified

Froude number for various modified phase ratios based on the new interpolating function, equation (9) is shown in figure 11. Table 5 shows the actual percentages collected in the intermediate scale tests of the single collector as well as the prediction from equation (9). For purposes of comparison, the results for the double and "riser only" collectors are presented in table 5 along with the predictions of equation (9) for a single collector operating at the same Froude numbers and phase ratios (based on total gas and liquid flows).

Concluding Discussion

A result of having done experiments at two different scales is that two scale-dependent effects were able to be identified and included in the smoothing function for fraction of blowout oil collected. With these included, the standard deviation between all single collector measurements, at both laboratory and at intermediate scales, and the new smoothing functions is 8.2%, which is probably representative of the overall experimental accuracy. It is anticipated that the new smoothing function as given by equations (9) and (10) is representative of full-scale collection efficiency for any anticipated gas/flow rate, riser flow rate and collector height.

The advantage of the double collector over the single collector has been clearly demonstrated in both laboratory and at intermediate scale. Under conditions where a single collector is efficient there is, of course, little to be gained by use of a double collector. However, under conditions where the efficiency of the single collector is rather low, very marked gains in collection efficiency are possible through use of a double collector. For conditions under which a single collector would collect less than 40% of the blowout oil, use of a double collector can result in collecting up to about twice as much oil.

Use of a riser alone without a collector has an efficiency that is approximately the same as a single collector. There are differences in the fluid mechanical details, however. Much more gas remains uncollected with the "riser only" system. Thus, the phase ratio in the system is higher than calculated for a single collector operating at the same collected liquid flow rate and wellhead gas/flow rate. Laboratory tests show that a small single collector which spills some of the gas, but less than a "riser only" system, is more efficient than either a "riser only" system or a single collector that spills no gas. Evidentally, there are two features of the "riser only" system whose effects on collection efficiency approximately counterbalance each other. One is the gain in efficiency associated with less gas in the collector entrance.

The other is the loss of efficiency due to some of the plume passing up beside and outside the riser.

The results of these studies clearly demonstrate that a large fraction of blowout oil can be collected with a sub-surface gas-lift driven collection system. The keys to a successful system are a sufficiently small distance between the wellhead and the collector and a sufficiently large diameter riser to achieve a high Froude number and a low phase ratio; and a means of separating the large amount of collected water from the oil at the surface. A straightforward analysis shows that the ideal surface component is a large tanker. Relatively rapid separation of bulk water from a water-in-oil emulsion takes place and each of the tanker's tanks can be used as a gravity separator for achieving this separation. The separated water can then be pumped overboard. This would allow a tanker to become completely filled with a water-in-oil emulsion which is expected to contain about 60% oil. Under typical blowout scenarios, such a tanker could remain on scene for about 1 week before becoming completely filled. Then it would have to be offloaded or replaced.

ACKNOWLEDGEMENTS

This work was supported in part by the U.S. Department of the Interior under contract number 14-08-001-20460 and in part by the Office of Naval Research under contract number N00014-81-K-0785.

References

1. Burgess, J.J., and Milgram, J.H., "Experiments with Scale Models of Oil Collectors for Subsea Well Blowouts", Jl. of Applied Ocean Res., 1983 , (in press)

2. Milgram, J.H., von Alt, C.J., and Burgess, J.J., "experiments with Scale Models of Oil Collectors for Subsea Well Blowouts - Part 2", Jl. of Applied Ocean Res., 1983 (in press)

Froude Number	Phase Ratio	Double Collector	Single Collector
0.009	0.033	86	36
0.014	0.18	81	39
0.018	0.66	95	69
0.019	0.35	90	52
0.021	0.26	68	54
0.022	0.10	47	35
0.022	0.21	58	53
0.066	0.30	82	75
0.072	0.16	70	63
0.14	0.64	94	59
0.17	0.22	90	88
0.17	0.37	94	93

Table 1. Laboratory Results for Tests With the Double Collector. The comparative single collector percentages are the predictions from equation (2) of ref 1 for the same Froude number and phase ratio.

Test Number	Height Above Wellhead (m)	Air Flow Rate (nm^3/s)	Dye Flow (liters/s)	Inner Riser Flow (m^3/s)	Outer Riser Flow (m^3/s)	% of Dye Collected
1	2.25	0.047	2.59	0.064	0.000	74
2	0.04	0.047	2.36	0.084	0.000	118
3	0.04	0.047	2.06	0.065	0.000	88
4	2.25	0.165	1.03	0.149	0.110	60
5	2.25	0.165	2.25	0.139	0.097	64
6	0.04	0.165	2.50	0.138	0.000	93
7	1.19	0.165	2.46	0.130	0.030	90
8	1.19	0.165	2.54	0.038	0.026	89
9	1.19	0.165	2.59	0.092	0.016	87
10	2.25	0.165	2.10	0.174	0.029	74
11	2.25	0.557	2.13	0.030	0.016	44
12	2.25	0.614	2.08	0.027	0.016	36
13	2.25	0.614	2.07	0.146	0.017	54

Table 2. Test Conditions for the Double Collector.

Test Number	Height Above Wellhead (m)	Air Flow Rate (nm^3/s)	Dye Flow (liters/s)	Riser Flow (m^3/s)	% of Dye Collected
1	1.19	0.047	1.08	0.102	87
2	1.19	0.047	2.10	0.104	84
3	0.04	0.047	2.13	0.102	100
4	1.72	0.047	1.37	0.104	80
5	0.04	0.165	2.28	0.136	88
6	1.19	0.165	2.26	0.138	80
7	1.19	0.165	2.25	0.079	63
8	1.19	0.165	2.25	0.040	56
9	0.64	0.165	2.25	0.136	96
10	0.64	0.165	2.25	0.039	57
11	0.64	0.165	2.25	0.077	91
12	0.04	0.550	1.99	0.147	94
13	1.19	0.590	2.13	0.115	65
14	1.19	0.590	2.11	0.051	32
15	1.72	0.590	0.88	0.155	40
16	1.72	0.590	0.95	0.052	14

Table 3. Test Conditions for the Single Collector.

Test Number	Height Above Wellhead (m)	Air Flow Rate (nm^3/s)	Dye Flow (liters/s)	Riser Flow (m^3/s)	% of Dye Collected
1	1.19	0.047	1.11	0.101	99
2	1.19	0.047	2.32	0.104	100
3	0.04	0.047	2.27	0.104	111
4	1.72	0.045	2.27	0.094	97
5	0.04	0.165	2.28	0.134	88
6	1.19	0.165	2.28	0.141	75
7	1.19	0.165	2.27	0.064	50
8	0.64	0.165	2.27	0.138	80
9	0.64	0.165	2.26	0.064	59
10	0.04	0.578	2.08	0.043	72
11	1.19	0.590	2.16	0.131	53
12	1.19	0.590	2.17	0.048	31
13	1.72	0.590	2.11	0.139	34
14	1.72	0.590	2.17	0.043	20

Table 4. Test Conditions for the Riser Alone Without a Collection Cone on Its Bottom.

DOUBLE COLLECTOR

NO.	F	R	TEST %	PREDICTED %
1	0.003	7.728	74.	42.
2	71461.875	9.737	118.	100.
3	55044.949	7.500	88.	100.
4	0.011	8.933	60.	67.
5	0.010	8.159	64.	64.
6	117332.625	4.579	93.	100.
7	0.034	5.270	90.	84.
8	0.031	4.770	89.	81.
9	0.023	3.510	87.	71.
10	0.013	3.153	73.	59.
11	0.004	0.874	44.	26.
12	0.003	0.651	36.	22.
13	0.012	2.569	54.	54.

SINGLE COLLECTOR

NO.	F	R	TEST %	PREDICTED %
1	0.023	12.120	87.	83.
2	0.023	12.322	84.	84.
3	87154.500	11.875	100.	100.
4	0.016	22.466	80.	80.
5	115884.125	4.523	88.	100.
6	0.031	4.684	80.	80.
7	0.017	2.674	63.	62.
8	0.009	1.366	58.	42.
9	0.172	4.550	96.	100.
10	0.044	1.314	57.	70.
11	0.086	2.571	91.	92.
12	125541.125	1.472	94.	100.
13	0.025	1.093	65.	55.
14	0.011	0.482	32.	32.
15	0.013	1.483	40.	48.
16	0.004	0.500	14.	23.

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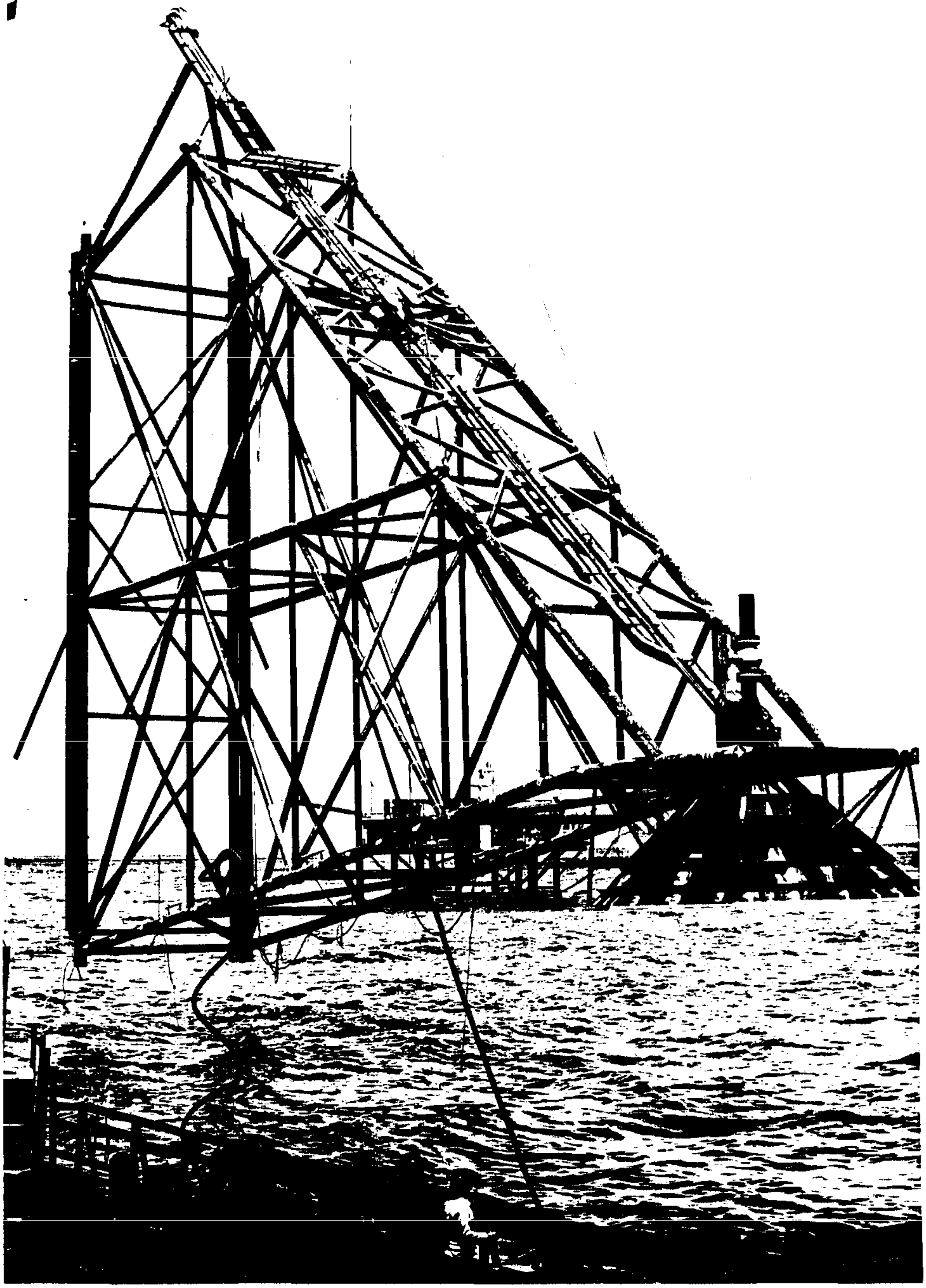
Table 5. Measured Percentages of Blowout Oil.
In addition to measured percentages for each condition, the Froude Number (F), Phase Ratio (R) and percentage predicted by equation (9) are shown. These are for a single collector so they provide a basis for comparison of the other systems.

Figure 1. Photograph of Full Scale Oil Collector Used at the IXTOC Oil Well Blowout



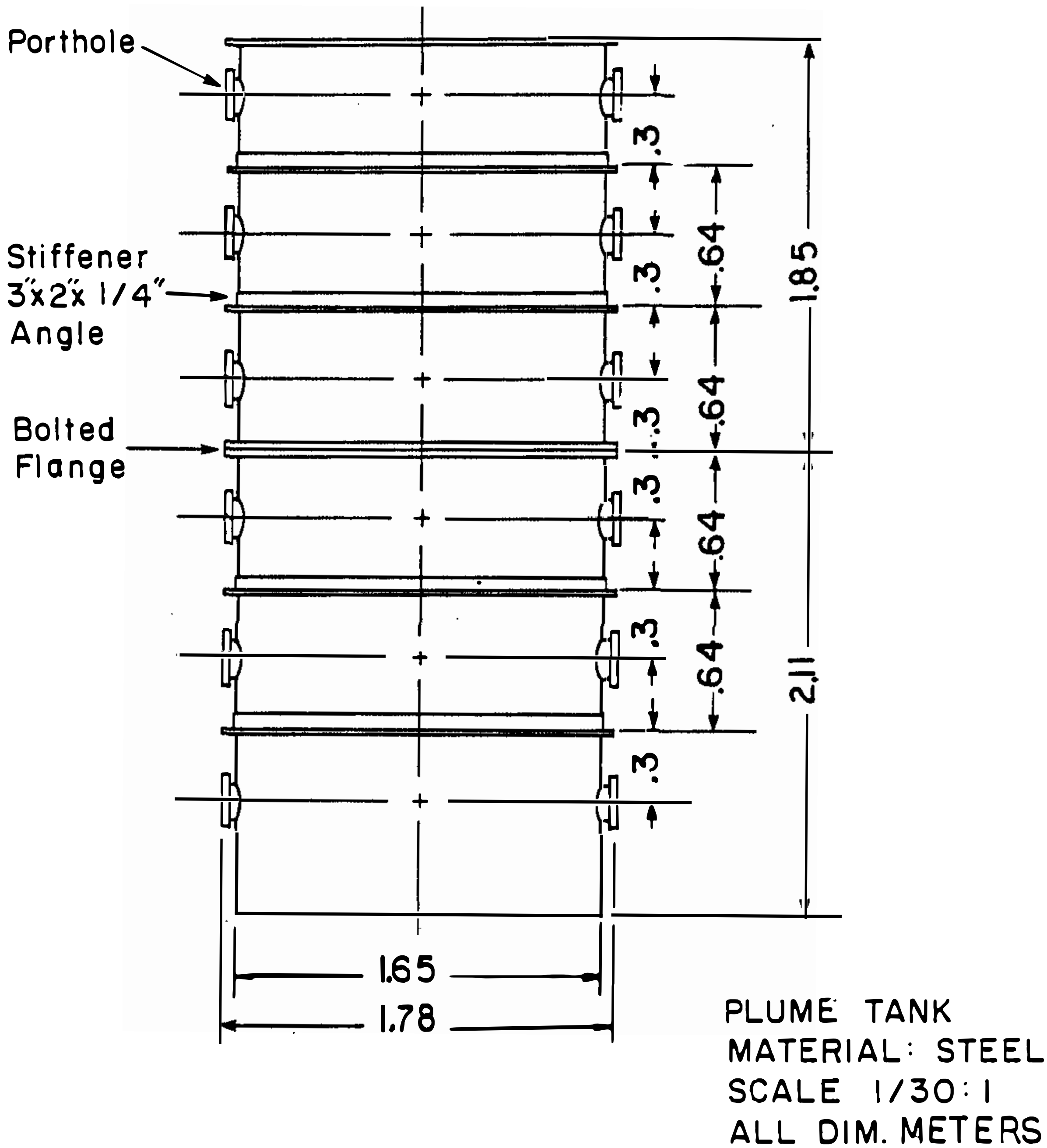
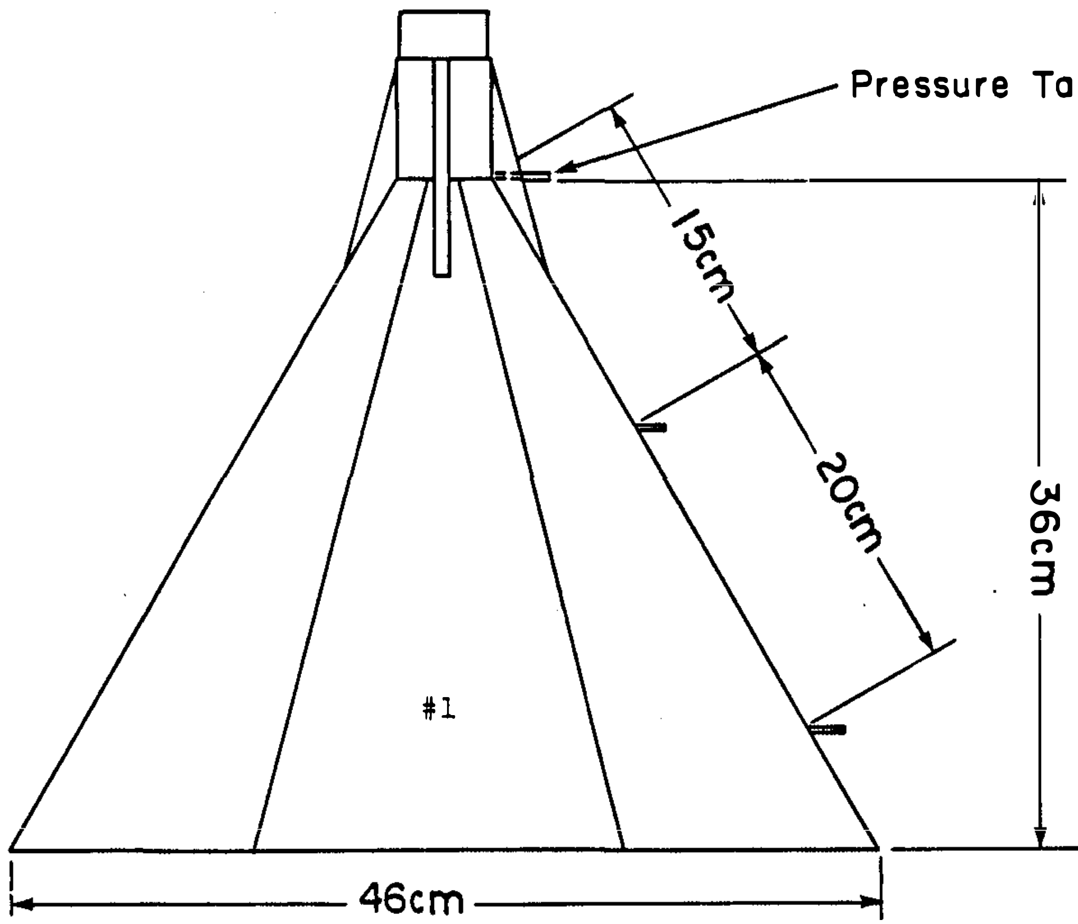
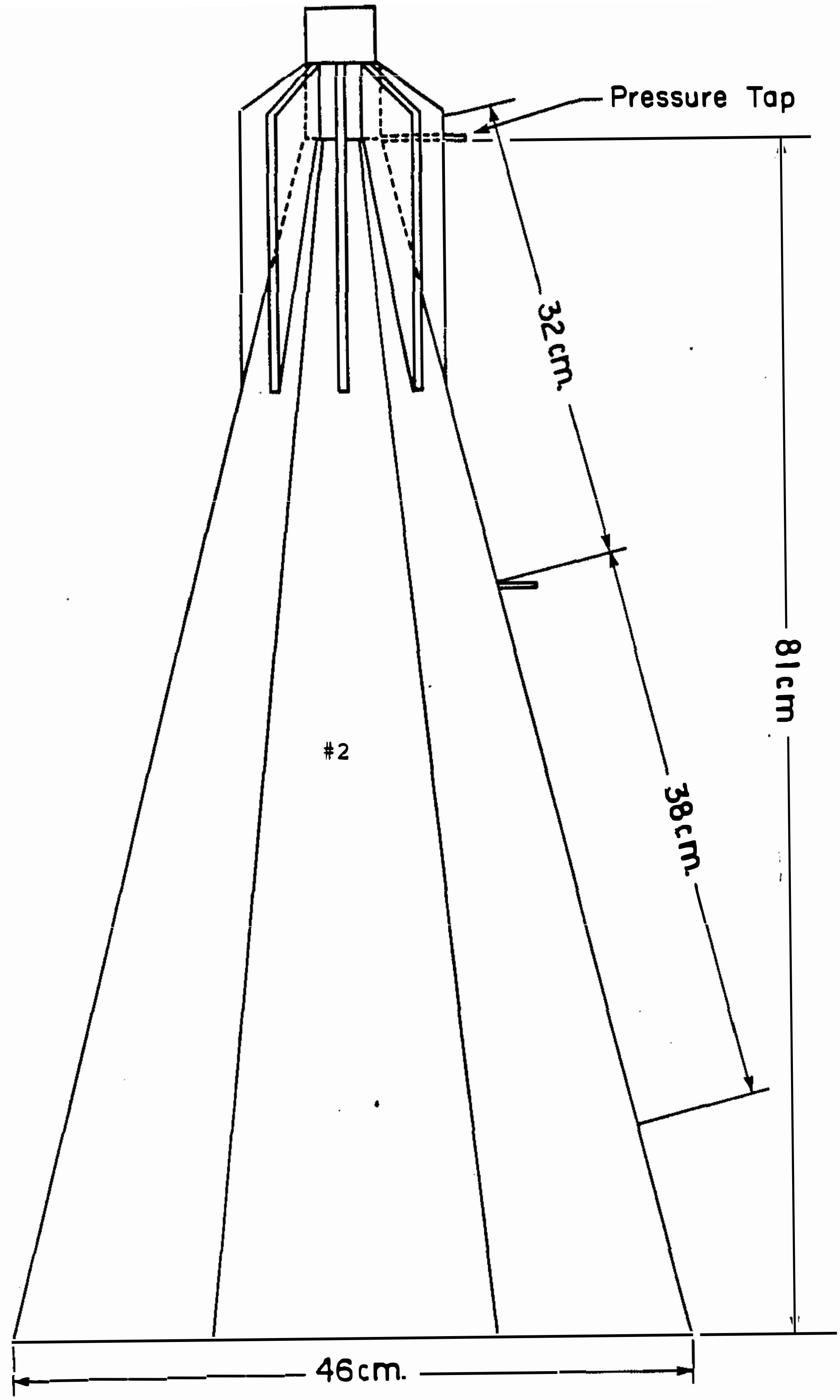


Figure 2. The Plume Tank Used for the Laboratory Experiments



3 a

Figure 3. The Collector Shapes Tested in the Laboratory



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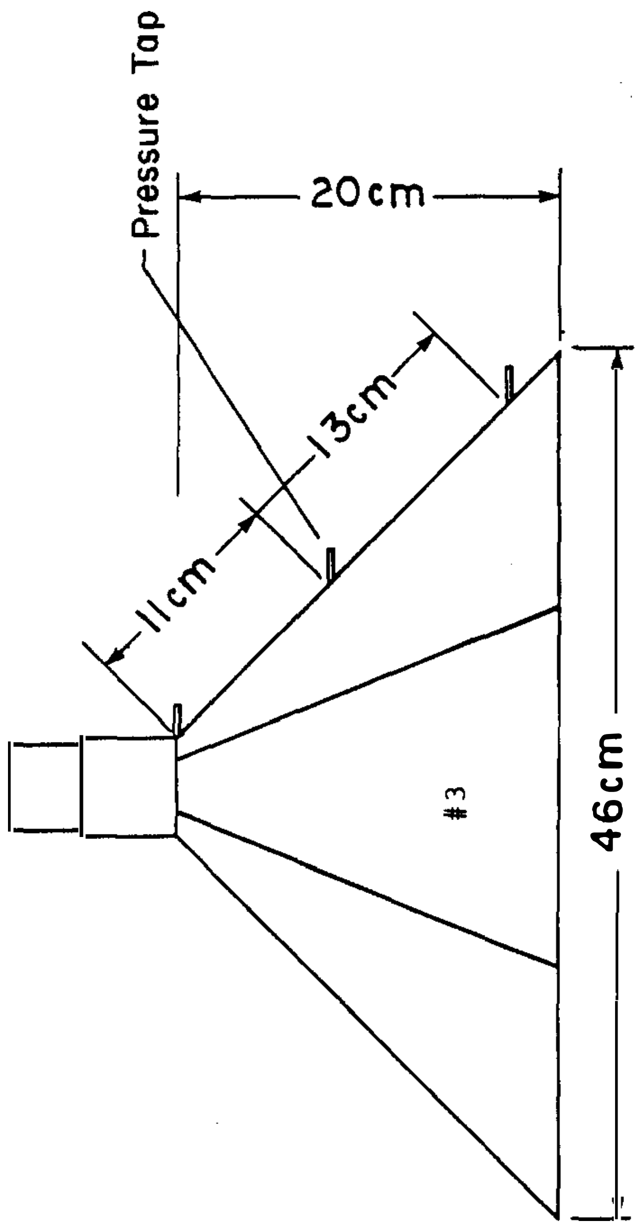
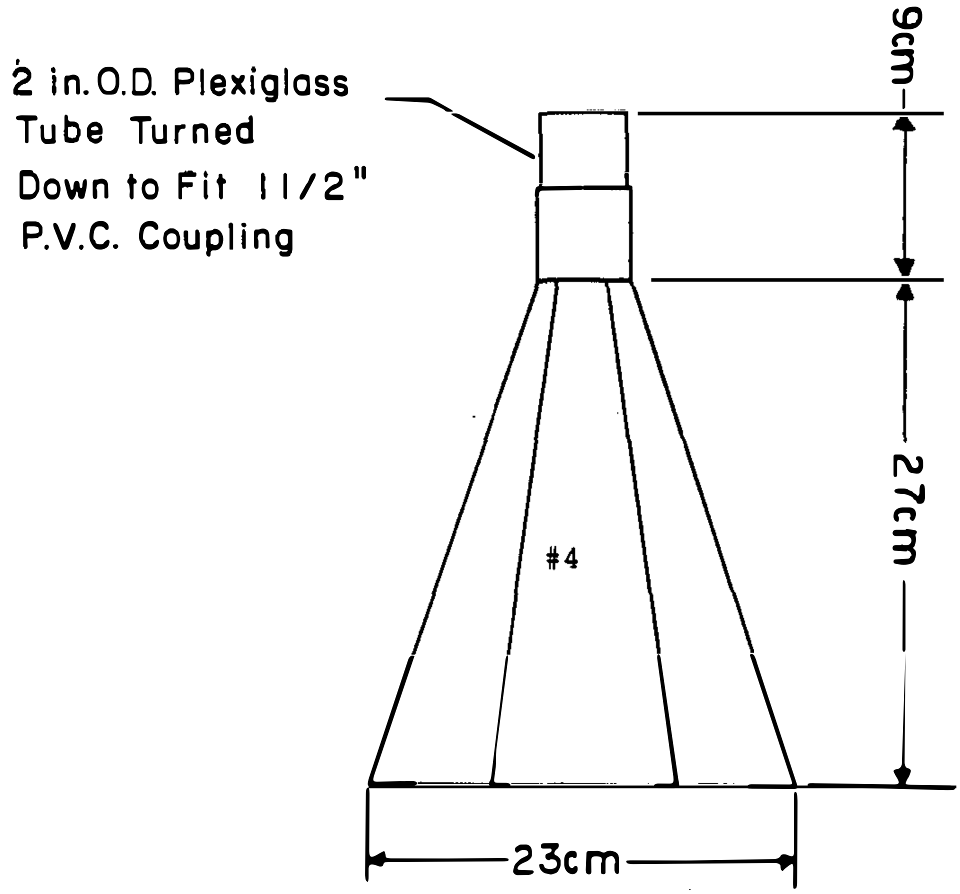


3 c


2 in. O.D. Plexiglass Tube Turned Down to Fit 1 1/2" P.V.C. Coupling
9cm
27cm
#4
23cm

3 d

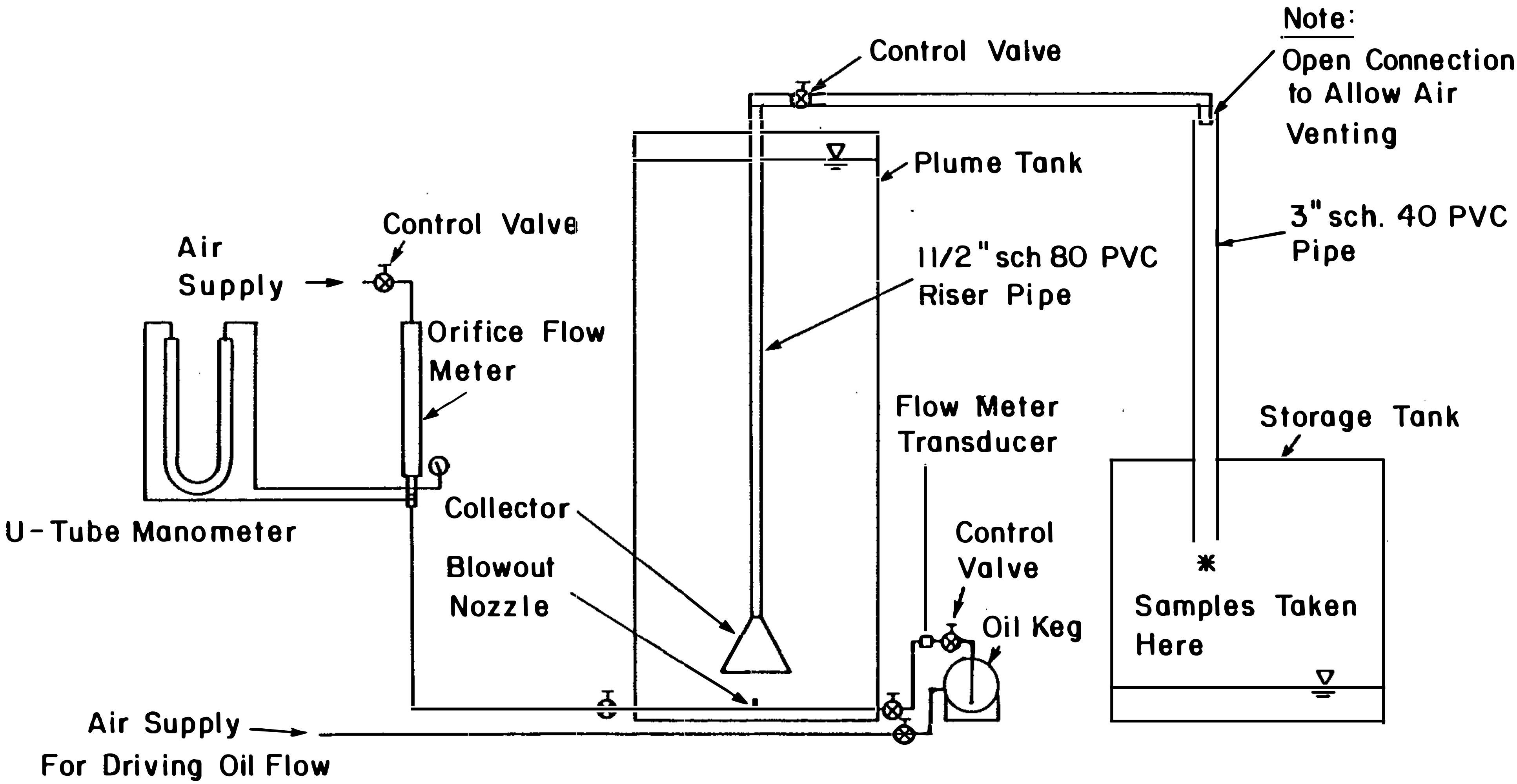


Figure 4. The Experimental Arrangement Used in the Laboratory

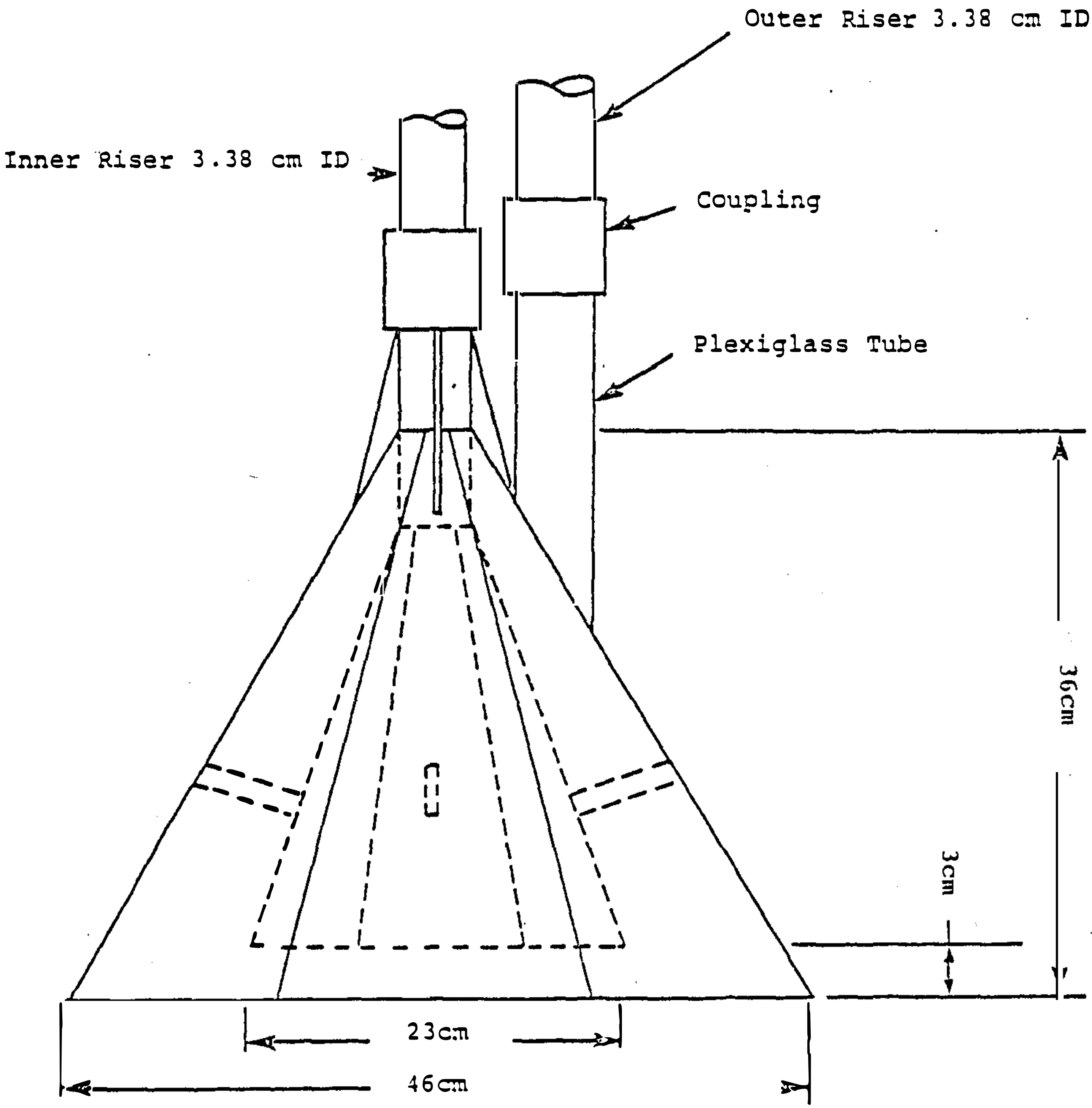


Figure 5. The Double Collector with Two Risers of the Same Diameter which was Tested in the Labortory.

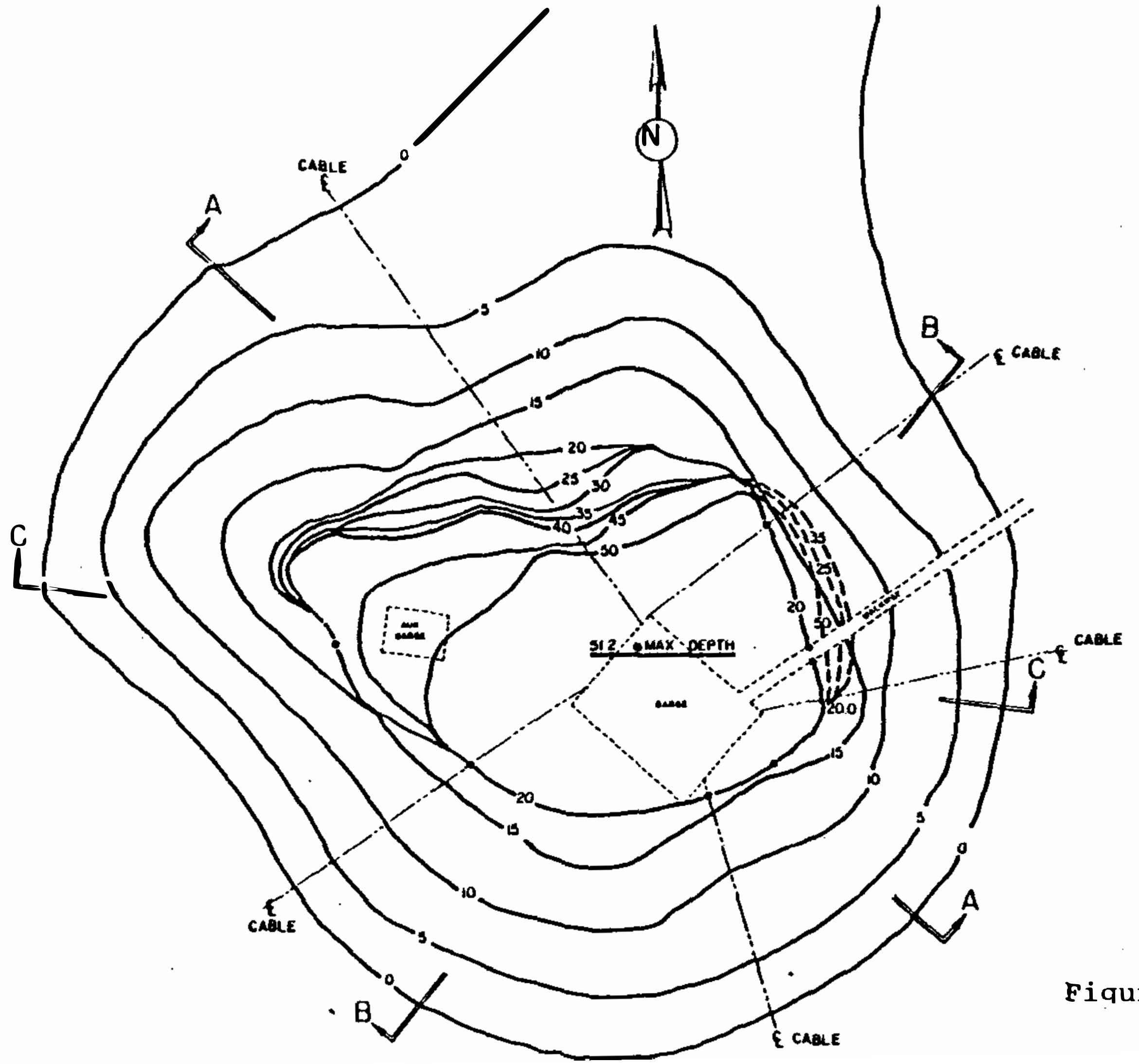
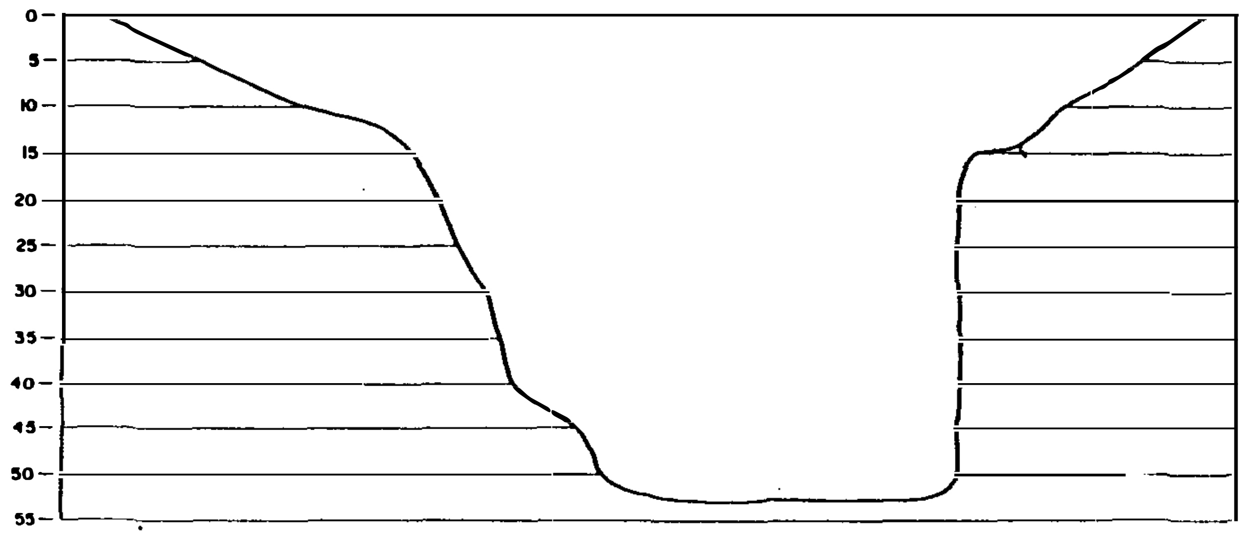


Figure 6. Drawings of Bugg Spring
(a) Plan View
(b) One Elevation View

PLAN VIEW

6 a



SECTION A-A

6 b

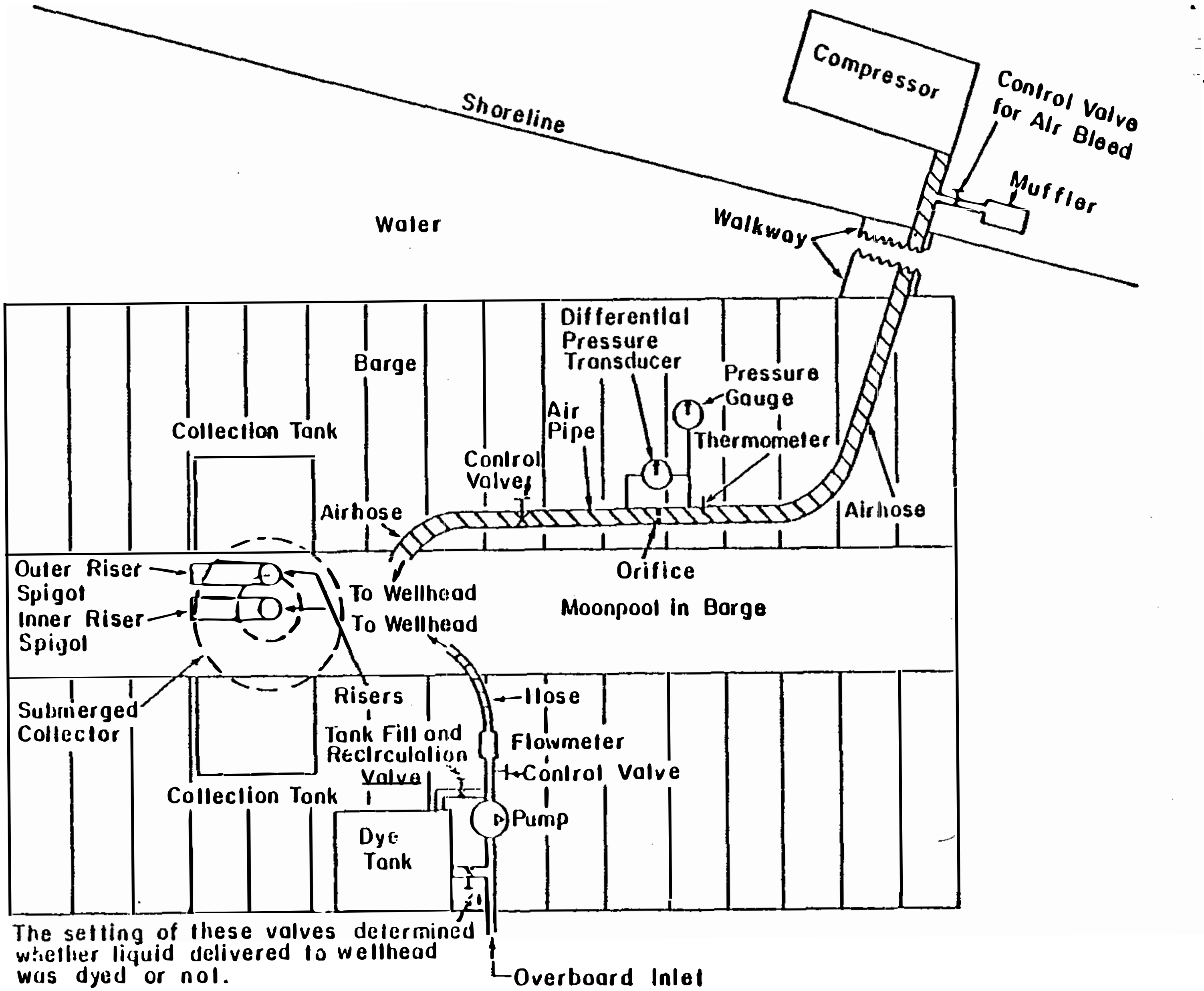


Figure 7. Overall Arrangement for the Intermediate Scale Tests.

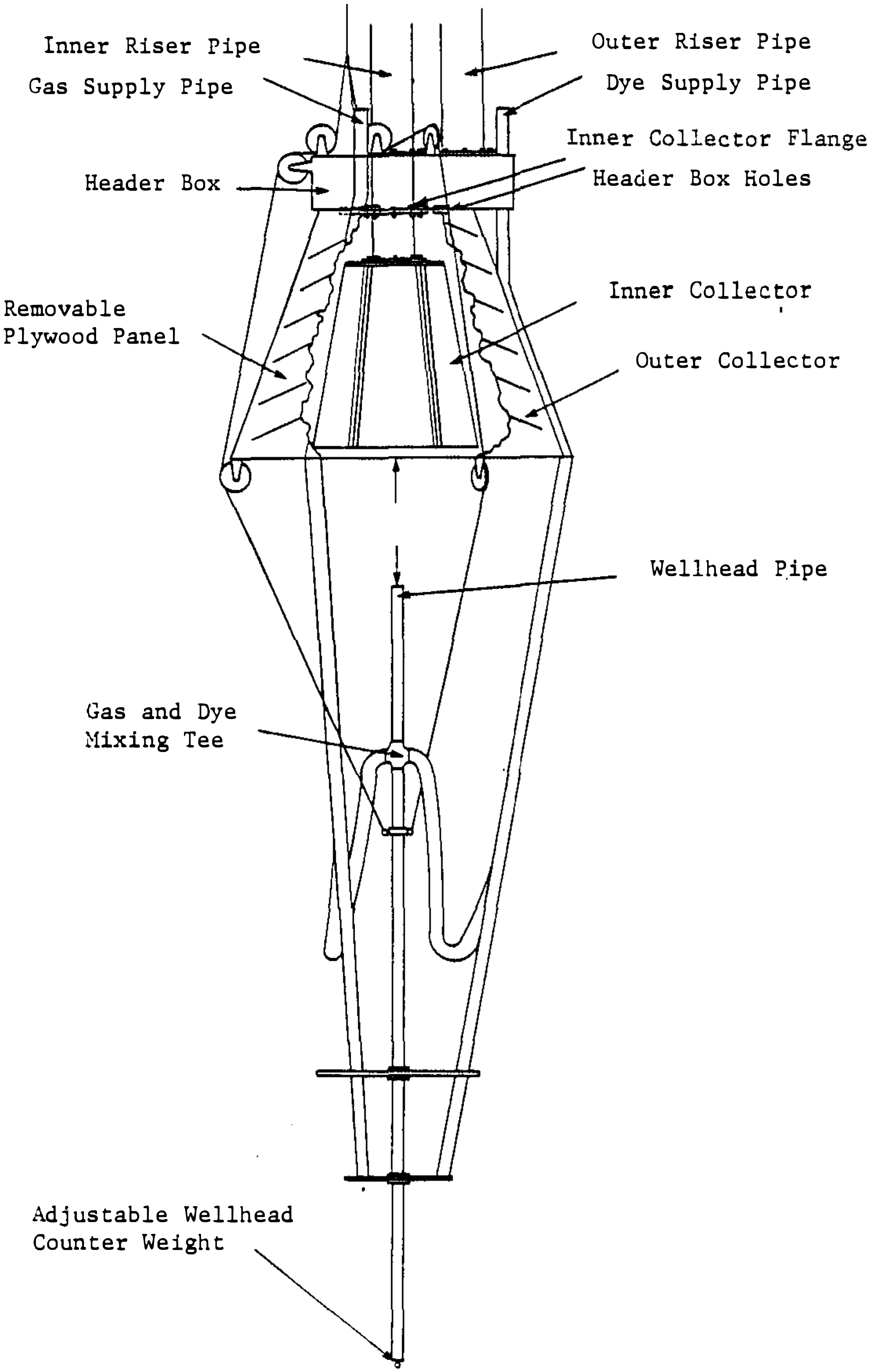


Figure 8. The Collector and Wellhead Assembly. This case is with the Double Collector.

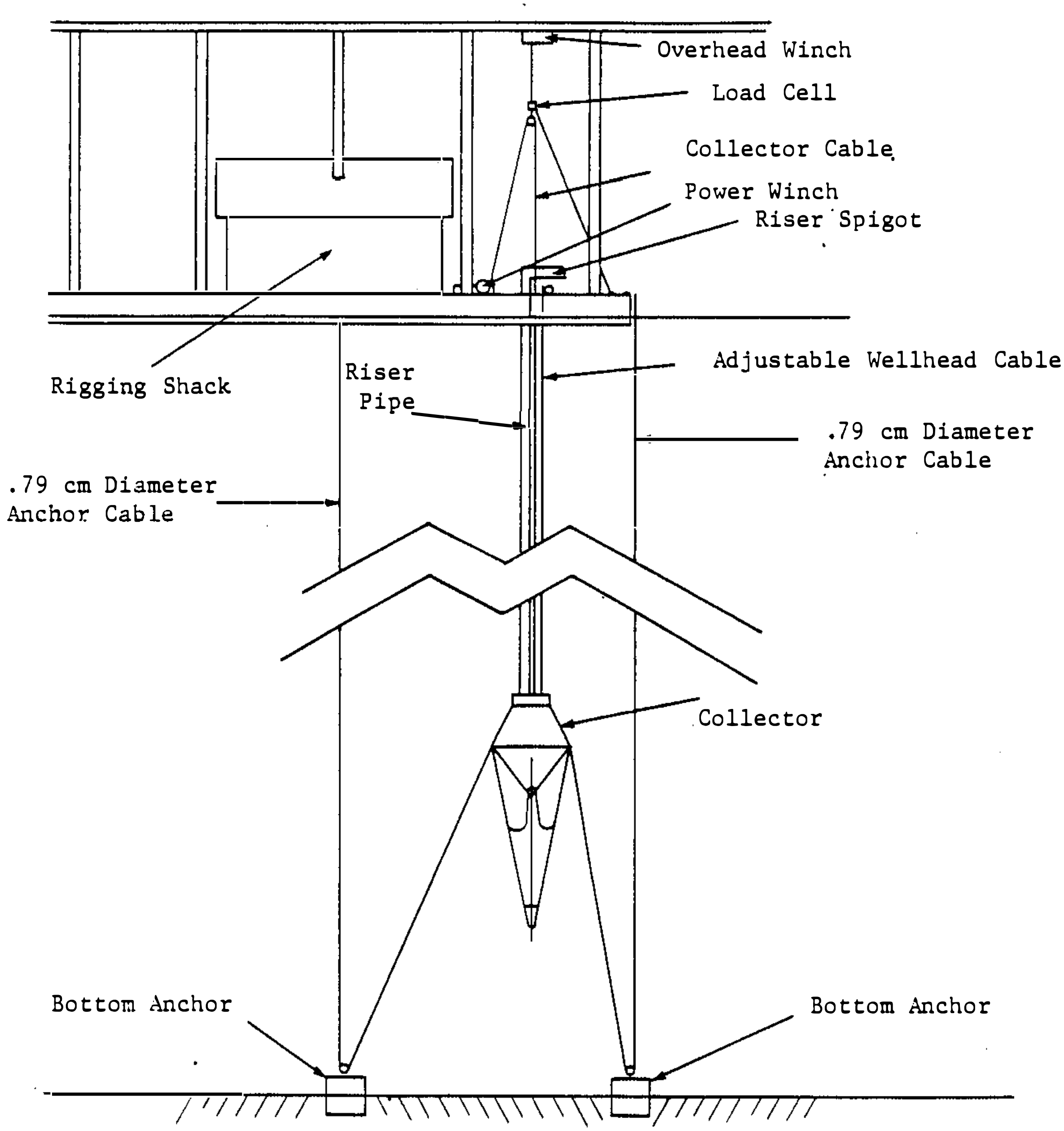
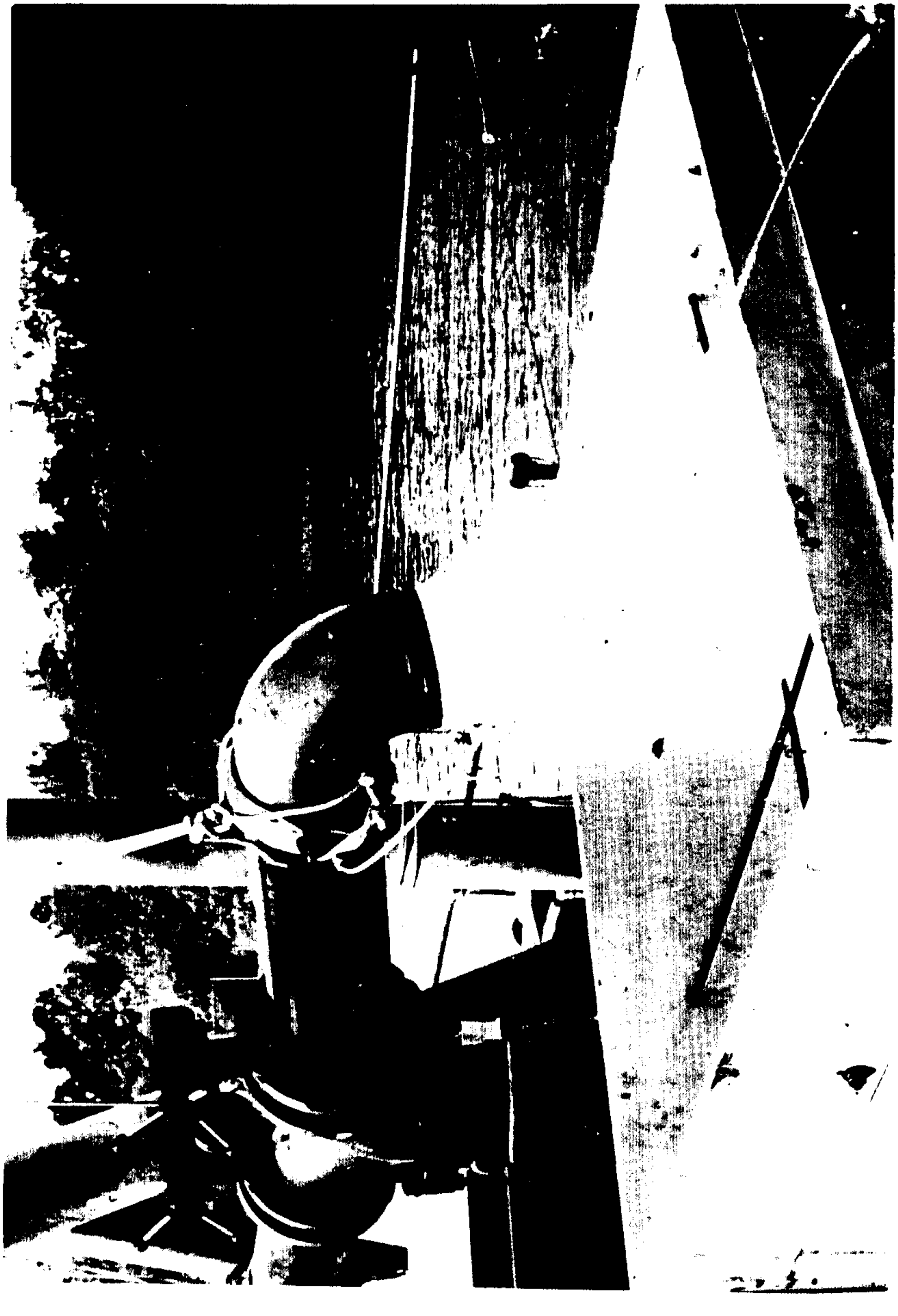


Figure 9. Mooring System. Three bottom anchors were used although only two are shown in this view.

Figure 10 The output flow from an operating Collector and Riser in the Experiments at Bugg Spring.



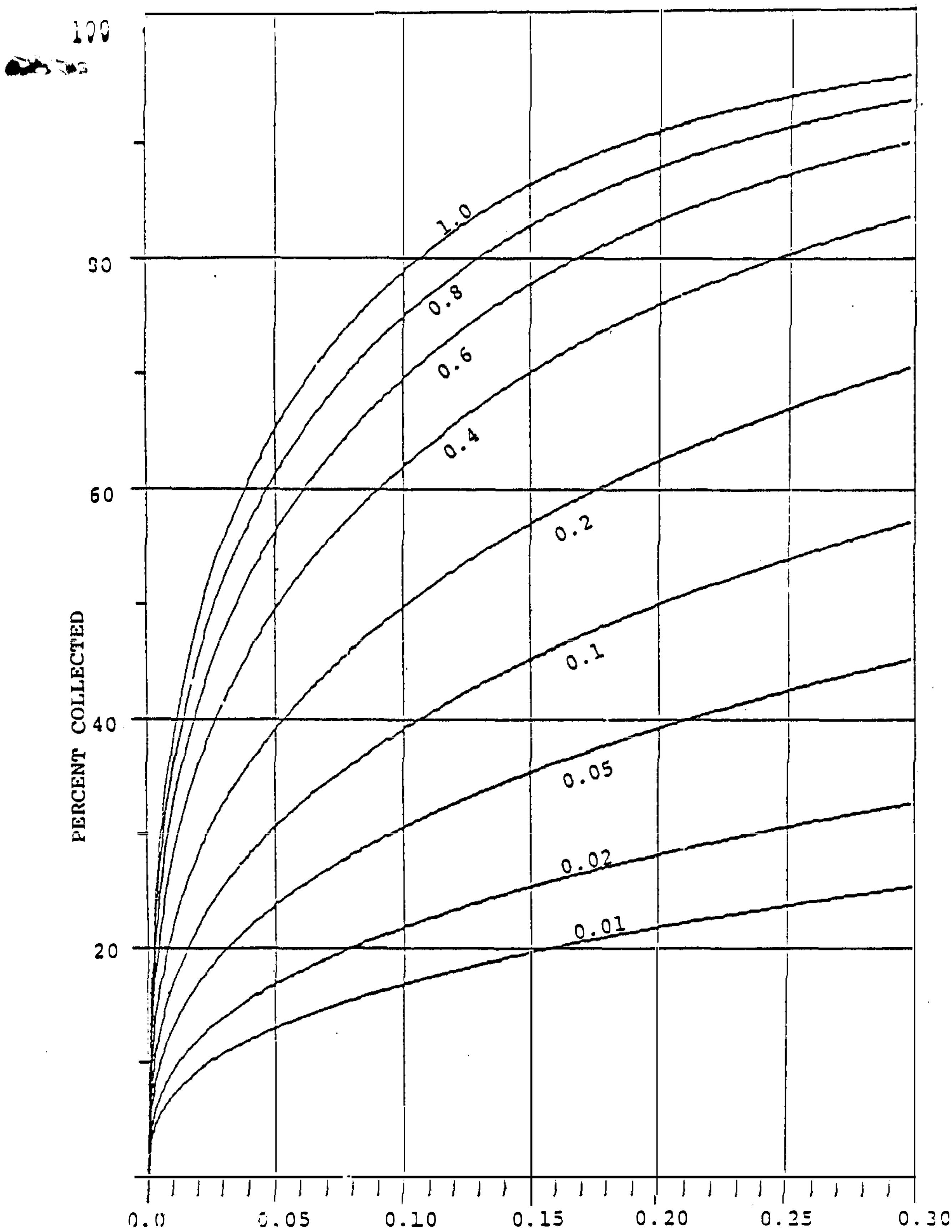


FIGURE 11. Percent Oil Collected vs. Modified Froude Number Using Equation 5.9 with: A'=59.69, B'=6.991 and C'=0.3726.

The number on each curve is the modified phase ratio, R'.