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Experiments with scale models of oil collectors for subsea well blowouts — Part II

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A previous paper of the same title indicated the feasibility of the collection of oil by an open bottom collector above a blowout with a marine riser above the collector; the whole collection system being driven by gas lift from the blowout gas. That paper was based on small-scale laboratory experiments and it identified the salient dimensionless parameters governing those experiments. This paper describes laboratory experiments on a refinement of the collection system and also describes the results of intermediate scale experiments. The length scale of these experiments was about four times greater than laboratory scale and about one-fourth of full scale. Generally, the intermediate scale results are consistent with the laboratory predictions. Furthermore, two scale-dependent parameters have been identified. The effects of these have been included in an analysis of the results.

1. INTRODUCTION

In Part I, authors Burgess and Milgram[1] described the results of laboratory scale experiments on subsurface oil collectors. The collectors were of the inverted funnel-type intended for use immediately above the wellhead or blowout source. It was found that the fraction of blowout oil collected was primarily dependent on the Froude number F, and the phase ratio R, with these quantities defined by:

$$F = Q_T/(gh^5)^{1/2} \qquad (1.1)$$

$$R = Q_T/Q_g \qquad (1.2)$$

where Q_T is the total collected liquid flow rate passing through collector and riser, Q_g is the gas volume flow rate, g is the acceleration of gravity, and h is the vertical distance from the blowout source to the base of the collector.

As the Froude number and phase ratio were increased the fraction of blowout oil collected increased. So long as nearly all of the blowout gas was collected, the fraction of blowout oil collected was relatively insensitive to details of the collector shape. When the collector was made small enough for a substantial portion of the gas to avoid collection by rising beside the collector, an increase in the fraction of blowout oil collected 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. As an aid in overcoming the reduction in collection efficiency resulting from excess gas, the gas separating collector described in Appendix B of Part I was devised. A few laboratory experiments with the gas separating collector are described in Part I. However, the range of test conditions was quite small and for that reason, some further experiments with the laboratory scale model of the gas separating collector were carried out and are described in the next section of this paper.

The laboratory scale experiments described in Part I have a length scale of approximately one-fifteenth of anticipated full scale. Complete dimensional similitude between laboratory scale and full scale does not exist with regard to Weber and Reynolds numbers. Perhaps the most important consideration with regard to scaling errors involves the gas bubble sizes which are approximately equal in the laboratory and in full scale. Therefore, the ratio of bubble diameter to riser diameter is substantial in the laboratory but very small at full scale. In order to assess the possible effects of scaling, larger scale experiments were conducted and are reported in this paper. For these experiments, the length scale is approximately one-fourth of anticipated full-scale lengths.

2. FURTHER EXPERIMENTS WITH THE GAS SEPARATING COLLECTOR

Figure 1 shows a drawing of the laboratory model of the gas separating collector. As is described in Part I, it was initially 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. In this condition, the interface between the continuous gas phase and the continuous water phase in the inner collector would be so low that nearly no liquid would pass through the central riser. The data presented in Appendix B of Part I were obtained for these conditions.

To operate a gas separating (henceforth called double) collector in the above 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 collector 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 the outer riser begins pumping. With both risers operating, the total collected

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4. INTERMEDIATE SCALE TEST APPARATUS AND EQUIPMENT

Figure 3 is a sketch of the layout of the experimental apparatus and equipment. This apparatus and equipment can be considered as five interconnected systems: the dye (simulated oil) system, the air (simulated gas) system, the collector and wellhead system, the mooring system, and the collection and analysis system. All of this equipment was on the barge except for the air compressor which was located on land because of its large size and weight. The various systems comprising the experimental arrangement are now described individually.

Dye delivery system

Because of environmental considerations, as well as other experiments that are done there, it was not feasible to pump oil into Bugg Spring. The fact that oil can be replaced by dye for measurements on the subsurface collectors was shown by the nature of the flow in the laboratory experiments. When leaving the wellhead, oil is broken down into very small droplets, typically having diameters much smaller than 1 mm. The amount of water collected far exceeds the amount of oil collected and the collected oil is distributed throughout the collected water by the extreme turbulence that exists in the flow. The oil can therefore be viewed as a 'tracer' for the water flow and any other tracer can be used for measurement purposes.

The dye used as a tracer for the intermediate scale tests was water soluble fluroscein. This dye was chosen because it can be quantitatively detected in extremely small concentrations by means of fluorimetry. In addition, any dye remaining in the spring water was ultimately broken down into colorless components by sunlight. The fluoroscein dye was mixed with water in 2 m^3 lots at a concentration of approximately 10 parts per billion. The water used in the dye mixture was pumped from the spring by a centrifugal pump through valving arrangements. This pump also circulated the dye mixture in the holding tank to ensure a homogeneous blend with valving to provide a means of pumping either the dye mixture or spring water to the wellhead during experimental tests. The quantity of the dye mixture pumped, simulating different oil flow rates, was adjusted by means of an in-line globe valve. The actual flow was measured using a Potter turbine flowmeter. The dye was pumped to the wellhead through a 3.8 cm inside diameter reinforced rubber hose.

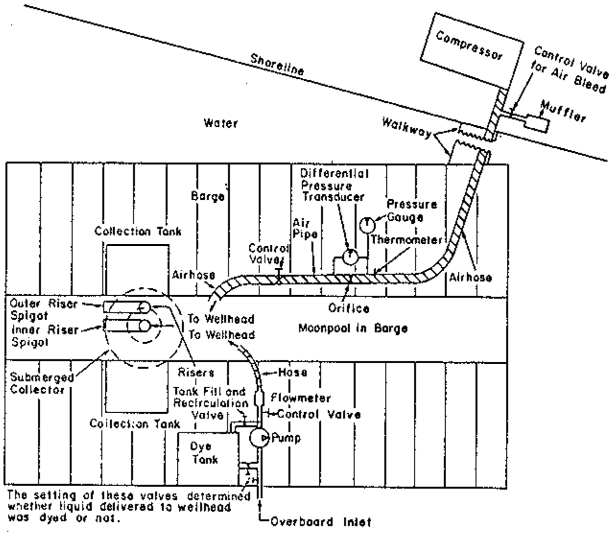

Figure 3. Overall arrangement for the intermediate scale tests

In the earlier laboratory scale tests, it was found that the fraction of blowout oil collected was independent of the blowout oil flow rate. This is consistent with the concept of the oil acting as a tracer in the water flow. Initial tests carried out with the intermediate scale collection systems also showed that the fraction of dye flow collected was independent of the dye flow rate. Following these tests, a nominal dye flow rate of 2.3 litres per second was used. The exact dye flow rate was measured during each test by the dye flowmeter.

Air delivery system

The blowout gas was simulated by air supplied from an Atlas Copco rotary screw oil-free diesel engine driven compressor rated at 0.71 standard cubic meters per second at pressures up to 8.5 atm. An oil-free compressor was chosen to avoid the introduction of oil-saturated air, normally associated with an oil-filled compressor, into Bugg Spring which contains abundant aquatic life. The compressor was controlled with a regulator which shuts off the air supply to its output tank when the regulator pressure setting is reached. The air supply is reinitiated after the tank pressure diminishes to a preset lower value. Thus in normal operation the compressor cycles and causes fluctuations in the air supply which could not be tolerated in our tests. To prevent this cycling the machine was always operated at its full output flow rate by bleeding off excess air. To minimize the noise from the air bleed jet, it was run through a muffler as shown in Fig. 3.

The air supply from the compressor was transferred to the barge and wellhead by a 7.6 cm inside diameter rubber hose. The air flow to the wellhead was set at desired rates by the simultaneous adjustment of a gate valve in the air bleed system and a globe valve in the air supply line. The air flow rate to the wellhead was monitored by the air temperature, the upstream pressure, and pressure drop across a square edge orifice meter mounted midway in a steel pipe 6.1 m long with a 7.6 cm inside diameter. The orifice meter and globe valve for adjusting the air flow rate were mounted on the deck of the barge with pipes and hoses running from them to the compressor and to the wellhead.

Collector, wellhead and riser system

The collector-wellhead assembly is shown in Fig. 4. In order to ensure that the wellhead remained centered with respect to the collector and that a means existed to vary the test variable h, the distance from the collector base to the wellhead, an adjustable wellhead assembly was attached to the base of the collector. In this configuration, the wellhead to collector base height could be varied from 0.04 to 2.0 m by adjusting a wire rope cable on the surface which ran down the riser and was attached to the wellhead through a system of sheaves. The collector base remained fixed at 46 m below the surface during all experiments and the wellhead height was varied by changing its depth. The internal diameter of the pipe forming the wellhead was 5 cm. The simulated gas and oil were mixed in the wellhead pipe at a tee joining two flexible hoses. The hoses were connected to the wellhead support frame made of pipe

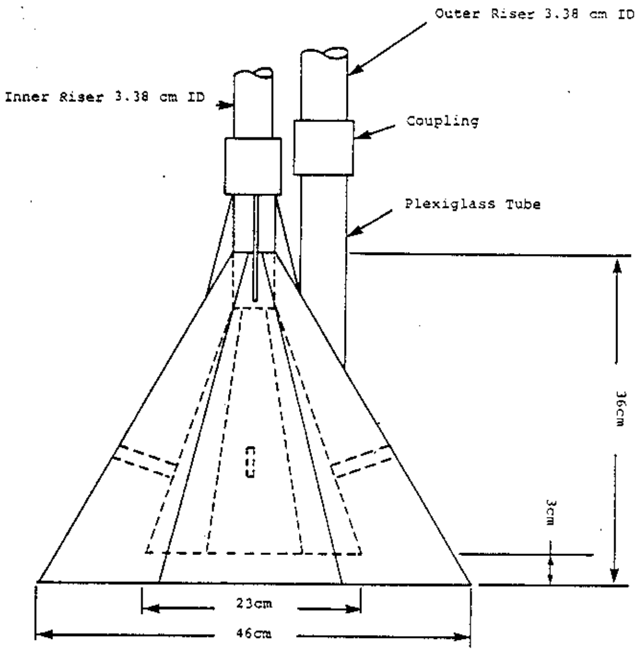

Figure 1. The double collector with two risers of the same diameter which was tested in the laboratory

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 riser 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 precisely the condition for which the double collector was initially designed.

To test the double collector in the 'automatic mode' described above, the model shown in Fig. 1 was fitted with two identical risers each having an inside diameter of 3.38 cm. Water and oil from each riser were collected and measured in the manner described in Part I and the Froude numbers and phase ratios were based on the sum of the liquid flow rates in the two risers. Table 1 shows the Froude numbers, phase ratios and oil collection percentages obtained for this series of tests. 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 (2) of Part I. That equation represents a numerical fit for all of the laboratory scale single collector data for which nearly all of the gas was collected.

3. FACILITY FOR THE INTERMEDIATE SCALE TESTS

Intermediate scale tests were conducted in Bugg Spring which is a natural sinkhole spring having a depth of 53 m and a mean surface diameter of 110 m. It is located at Okahumpka, Florida, and is part of the US Naval Research Laboratory. The spring is isothermal maintaining a temperature of 22°C during the entire year. Fresh water enters through the bottom in a distributed fashion and leaves by a stream at one end at a low enough flow rate for there to be no discernible water currents in the test area.

Figure 2(a) shows a contour plan and 2(b) a cross-sectional depth profile of Bugg Spring. The contour plan shows the position of a tightly-moored barge which served as the work platform for the experiments.

Table 1. Laboratory results for tests with the double collector. The comparative single collector percentages are the predictions from equation (2) of Part I for the same Froude number and phase ratio

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

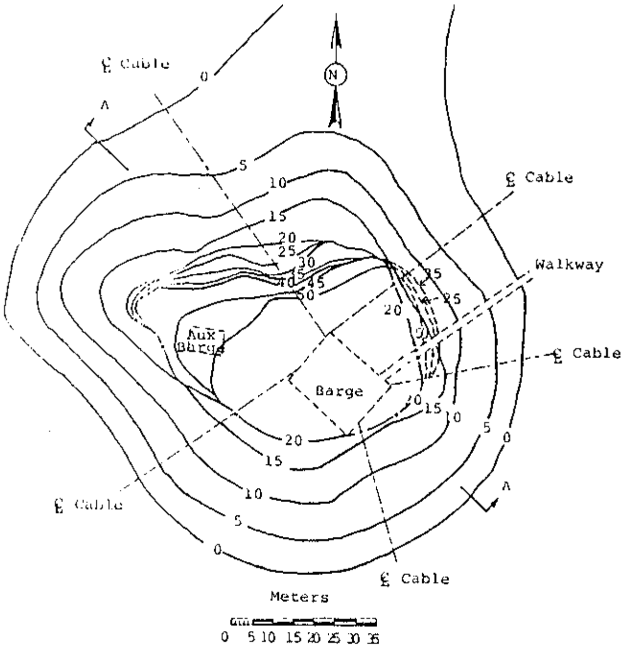

Figure 2(a). Contour plan of Bugg Spring

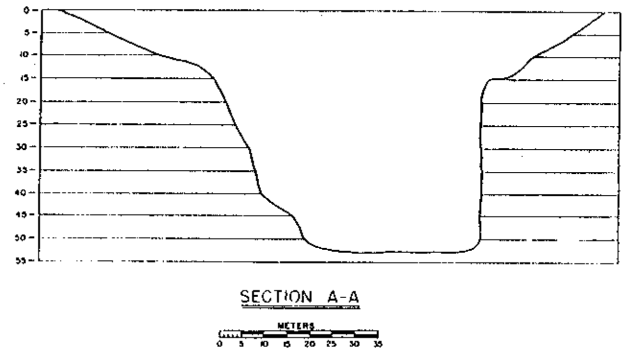

Figure 2(b). Cross-sectional depth profile of Bugg Spring

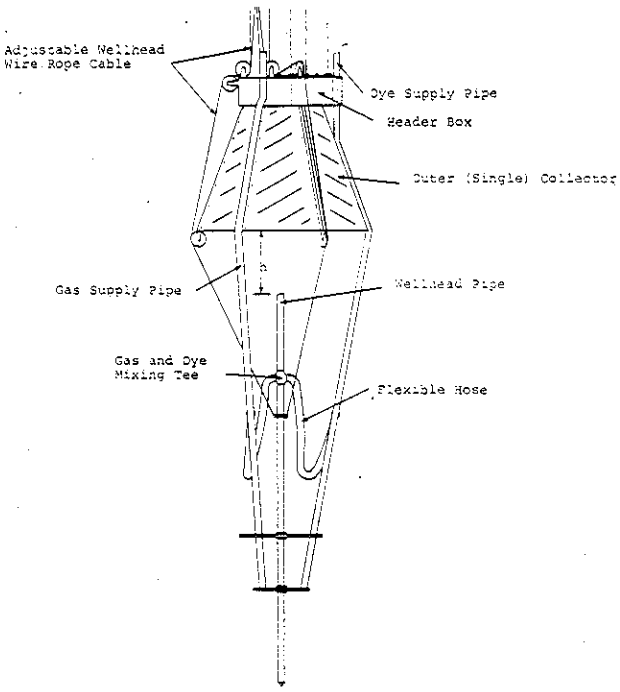

Figure 4. Collector wellhead assembly with single collector

which also served as a means of conducting the simulated oil and gas from the wellhead assembly to the flexible hoses.

During the intermediate scale model experiments, 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 held the same scale in that its internal diameter was the same as the riser pipe used for the single and double collectors. Laboratory scale tests indicated that a riser alone could collect a significant percentage of blowout oil. The use 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. Therefore this configuration was included in the test program.

One major structure, the outer-single collector and header box, was constructed to accommodate all three different collector configurations. This structure also incorporated pipes which transported the simulated oil and gas, from the hoses lashed to the risers, to the wellhead. Figure 5 shows the details of the double collector. The inner collector was bolted to a flange which was attached to a pipe that ran through the header box and formed the inner riser. The outer collector, which also formed the single collector, was built under the header box which had six 10.2 cm diameter holes in its bottom. These holes allowed the passage of gas and liquid from the outer collector of the double collector system into the outer riser pipe bolted to the top of the box.

During the testing of the single collector, the inner collector from the double collector system was unbolted from the inner flange, thereby forming a single collector. The holes in the bottom of the header box were plugged with pipe plugs. The inner riser pipe of the double collector then became the single collector riser and the outer riser was removed from the system.

To test the straight riser pipe, the six plywood side panels of the single-outer collector were removed. This condition left a steel support frame so that the wellhead remained supported. A 20 cm diameter pipe 1.2 m long, which equaled the collector height, was bolted to the inner flange on the bottom of the header box. This pipe then served as the riser pipe collector. Figure 6 shows the riser pipe collector configuration.

The riser pipes, which ran from the top of the header box to the surface, were made of 6063-T6 aluminum. The pipe came in 6.1 m long sections and had an internal diameter of 20.32 cm and a wall thickness of 0.32 cm. The sections of riser pipe were held together with Victaulic couplings. The riser system contained a 0.95 cm wire rope cable attached to the top of the collector, the 3.8 cm internal diameter dye system hose, the 7.6 internal air system hose, and one or two 20 cm pipes, depending upon which collector configuration was being used. The cable and hoses were lashed to the outside of the risers.

On the top of each riser, a swivel joint was incorporated into the system which allowed the riser spigots to be rotated in a horizontal plane so that liquid flow rates could be determined by measuring collected volume and time. Above the swivel joints, each spigot was formed by a 90° elbow with a pressure gauge mounted in it, followed by a butterfly valve for adjusting riser resistance. Each valve was followed by a section of pipe approximately 1.3 m long which was connected to another 90° elbow to direct the flow downward. The entire system had an internal diameter of 20.3 cm.

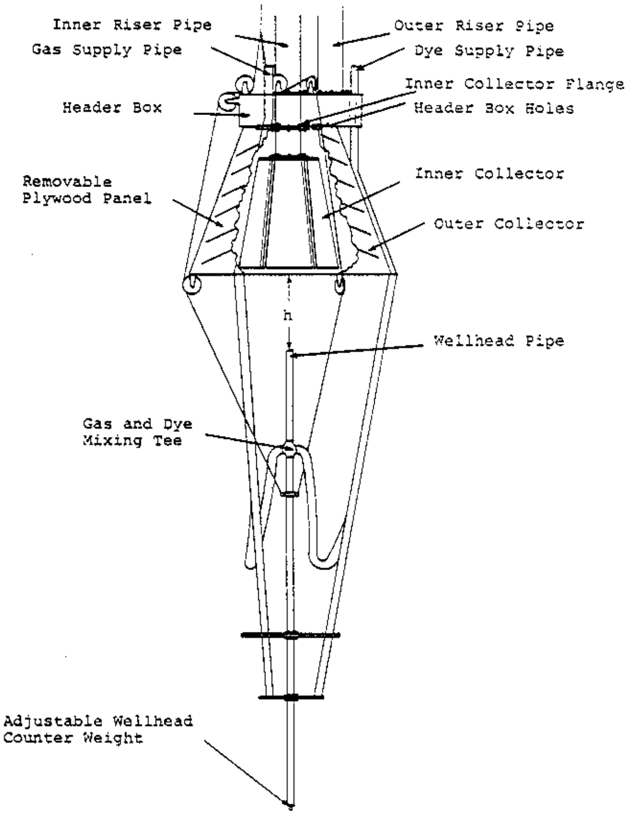

Figure 5. Details of double collector

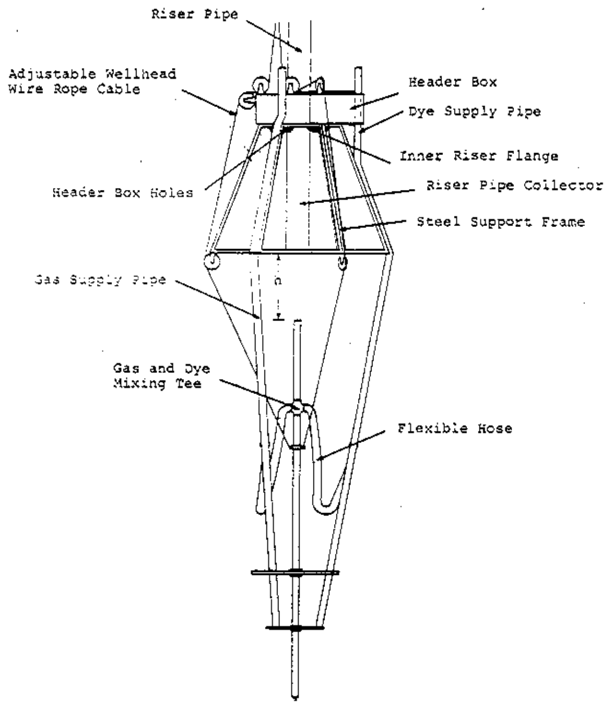

Figure 6. Single riser pipe collector

Mooring system

If the entire double collector system including its two risers became filled with air, it would develop a buoyancy of approximately 5 tonnes. Although this condition was never expected to occur during the experiments, the heaviest practical mooring system was devised. As shown in Fig. 7, the collector system was anchored to the bottom by three moorings. Each anchor had a weight in water of approximately 1.4 tonnes. Each anchor weight was connected to the collector by a 0.79 cm diameter cable which ran through a sheave on the top of the anchor weight and then to the surface where it could be let out and hauled in as desired. A fourth wire rope attached to the top of the collector ran to the surface and then through a sheave in a gantry on the barge and on to a power winch. By slacking off or taking in the anchor lines, the collector system could be raised or lowered. During the collector tests, the mooring system was placed in tension by making fast the three anchor lines attached to anchor weights and by taking up on the power winch until 1 tonne of line force was attained. The tension in the system and relative buoyancy of the collector system were monitored by a load cell mounted above the gantry sheave as shown in Fig. 7.

Collector and analysis system

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 liquid collection rate was determined from the time required to collect a known volume of liquid. Two open top tanks having a volume of 1.9 m^3 were constructed and installed on the barge. These tanks were fitted with sight glasses and were calibrated with a volume scale on each sight glass. One tank served each of the riser spigots. To measure a volume flow rate, a spigot was swung over a tank for a measured time interval and the collected volume during this interval was measured.

Dye concentrations were measured with a Farrand Model A-4 fluorometer. This instrument was fitted with a 490 nm interference filter for excitation of the sample and a Farrand Model 3-69 filter for the sample emission. Details of the dye concentration determination procedure are given in the next section.

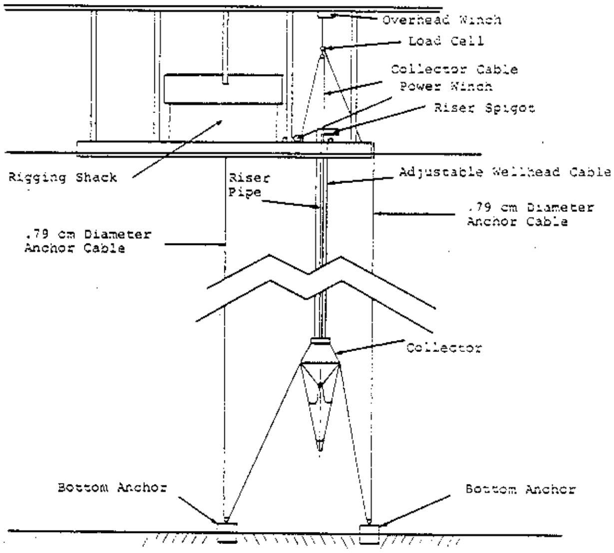

Figure 7. Mooring system. Three bottom anchors were used although only two are shown in this view

Table 2. Test conditions for the double collector

Test number	Height above wellhead (m)	Air flow rate (nm³/s)	Dye flow (liters/s)	Inner riser flow (m³/s)	Outer riser flow (m³/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

5. TEST PROCEDURES

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. Each test was initiated by setting a nominal air delivery rate to the wellhead. A nominal liquid flow rate was set by the dye system control valve, but at this time dye was not delivered to the dye pump. Rather, the inlet of the pump was supplied from the Bugg Spring water itself so that operating conditions could be first established without any dye tracer in the flow. The riser valves were adjusted to provide the desired riser resistance.

After gaslift pumping was established, the system was allowed to operate in this condition for several minutes to flush any dye from previous tests out of the riser and collectors. Next, samples of the water delivered by the riser spigots were taken to be later used in the analysis for the fraction of blowout dye recovered by the collection system. The inlet to the dye delivery pump was then switched to the dye tank so that a dye stream was provided to the wellhead. The system was allowed to operate in this fashion for 2 min which was long enough to allow the liquid in the risers to be exchanged several times and thereby insure that dye concentrations delivered by the riser spigots were the same as the concentrations of the material collected by the collectors. During this time actual air flow rates, as determined by the orifice meter, and dye flow rates, as determined by the dye flowmeter, were recorded. In addition, a sample of the dye solution in the dye tank was taken to be used in the analysis. After the 2-min time period was completed, collected liquid samples were taken. In the case of the double collector, this involved using the two riser spigots and the two collector tanks, whereas tests with either the single collector or the riser alone without a collector involved a single riser spigot and a single collection tank. The spigots were swung over a collection tank and a stopwatch was started. After approximately 1.5 m^3 were collected in a collection tank, the riser spigot was swung away and the stopwatch was stopped. The collection flow rate from each riser was determined by dividing the stopwatch time into the volume of the collected liquid. Samples of the collected liquid were taken from the collection tanks for subsequent analysis. Figure 8 is a photograph of an operating riser spigot. (See overleaf.)

Table 3. Test conditions for the single collector

Test number	Height above wellhead (m)	Air flow rate (nm^3/m)	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 4. Test conditions for the riser alone without a collection cone on its bottom

Test number	Height above wellhead (m)	Air flow rate (nm^3/m)	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

6. DATA ANALYSIS

Determination of the fraction of blowout liquid that was collected

The goal for this portion of the data analysis is the determination of the fraction of the dye delivered by the wellhead that was collected for each test case. This is taken as representative of the fraction of oil from a blowout that would be collected for similar conditions.

The following symbols will be used for a single riser system:

c_d = dye concentration in dye tank
c_a = dye concentration in collected liquid
Q_d = liquid flow rate of dye delivered to the wellhead
Q_a = liquid flow rate in riser

For the double collector system which contained two operating risers, all of the above variables apply with the subscript a referring to quantities associated with the inner riser and with the addition of the following quantities:

c_b = concentration of dye in liquid coming from outer riser
Q_b = liquid flow rate in outer riser

For the single riser system, the fraction, f_a, of blowout liquid collected is given by:

$$f_a = \frac{c_a Q_a}{c_d Q_d} = \frac{c_a}{c_1} \tag{6.1}$$

where the reference concentration c_1 is given by:

$$c_1 = c_d(Q_d/Q_a) \tag{6.2}$$

For a double riser system, f_a is the fraction of blowout oil collected by the inner riser with the fraction collected by the outer riser being given by:

$$f_b = \frac{c_b Q_b}{c_d Q_d} = \frac{c_b}{c_2} \tag{6.3}$$

where the reference concentration c_2 is given by:

$$c_2 = c_d(Q_d/Q_b) \tag{6.4}$$

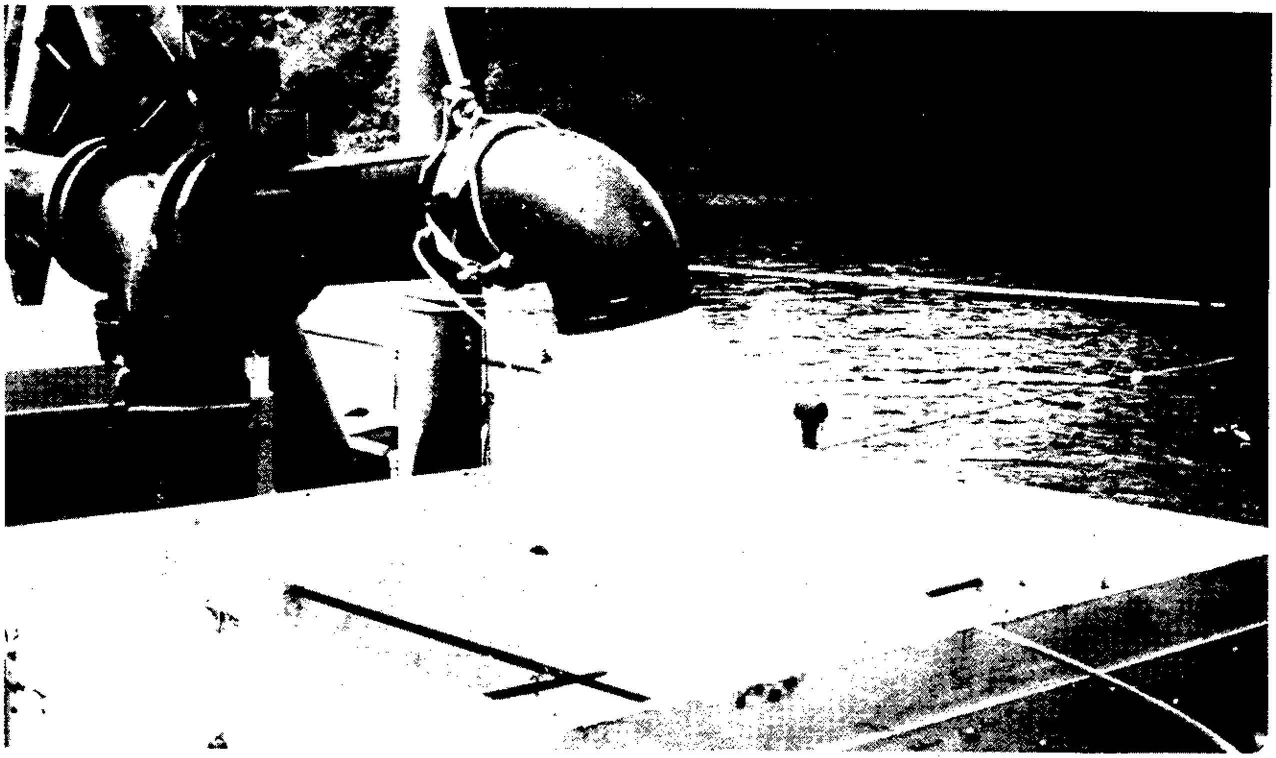

Figure 8. An operating riser spigot. The riser flow is emptying into the tank used for measuring flow rate. The adjustable riser resistance control valve can be seen. Also the control valve and part of the spigot for the second riser can be seen

The fluorometer was set up to provide a measure of the concentration of a sample with respect to two reference concentrations c_l and c_u. The concentration scale that these provide is 0 for c_l and 1.0 for c_u. For each measurement, the collected water sample before dye pumping began was used for c_l. These are called 'bottom water samples'. The value used for c_u in each measurement was either c_1 or c_2, as given by equations (6.2) and (6.4), depending on which riser flow was being analyzed. These samples, having concentrations c_u, were prepared by diluting the sample of dye tank liquid with the bottom water sample according to the dilutions specified by equations (6.2) and (6.4).

In the case of the double collector system, the total collected fraction for each case was determined by adding f_a and f_b. The collected blowout liquid percentages (100× collected fraction) are shown in Table 5 along with the test flow rates.

Data reduction

For each test condition, the Froude number and phase ratio were calculated in accordance with equations (1.1) and (1.2). The liquid flow rate from each riser was known by dividing the sample-taking time into the amount of liquid collected during that time interval. For the double collector system, the two riser flow rates were added together to determine Q_T. The gas flow rate was taken from the orifice meter readings and calculations. This is representative of the gas flow rates within the systems having collectors. However, for the test having only a riser without a collector on its bottom some of the gas escaped beside the riser so that the average phase ratio in the riser is higher than the calculated values for R with this particular system.

The data interpolation function given by equation (2) of Part I is based on a phase ratio determined from the gas flow rate at a pressure of 1 atm. That interpolation function is satisfactory for all of the measurements described in Part I 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 that influences the fluid mechanics in 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 atm multiplied by the ratio of 1 atm to the absolute pressure at the collector entrance. In order to adjust equation (2) of Part I for phase ratios calculated in this way, it is only necessary to modify the coefficient B to its 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 for B of 1.41879 for use with air flow rates at the surface becomes 1.88699 for use with air flow rates at the collector entrance.

It was noted in Part I that when the interpolating function was applied to all of the laboratory data on which it was based, the standard deviation between percentage of oil collected and the percentage predicted by the interpolating function was 8.7%. When the same interpolating function, adjusted for utilizing air volume flow rate at the collector entrance, was applied to the intermediate scale data for the single collector, the standard deviation between predicted percentage collected and the actual percentage collected was 10.9%. A study was made to determine why this was larger than the 8.7% found with the laboratory 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 scale-dependent phenomena were identified.

The values found for the coefficients are:

$$A' = 59.69$$
$$B' = 6.991$$
$$C' = 0.3726$$
$$D' = 0.1112\,\mathrm{m}$$
$$E' = 11.77 \qquad (6.10\mathrm{a,b,c,d,e})$$

The standard deviation over all of these data points between the interpolating function and the measurements is 8.2% which is an improvement over the 8.7% for the application of the weighting function in Part I to only the laboratory scale data. In applying the new interpolating function to the intermediate scale data only, the standard deviation is 8.4%.

A set of smooth curves of fraction collected versus Froude number for various phase ratios has been prepared from the new interpolating equation (6.9). It is shown in Fig. 9. Table 5 shows the actual percentages collected in the intermediate scale tests of the single collector as well as the predictions of equation (6.9) for each test condition with the single collector. For purposes of comparison the results for the double and 'riser only' collectors are presented in Table 5 along with the predictions of equation (6.9) for a single collector operating at the same Froude numbers and phase ratios (based on the total liquid and gas flows).

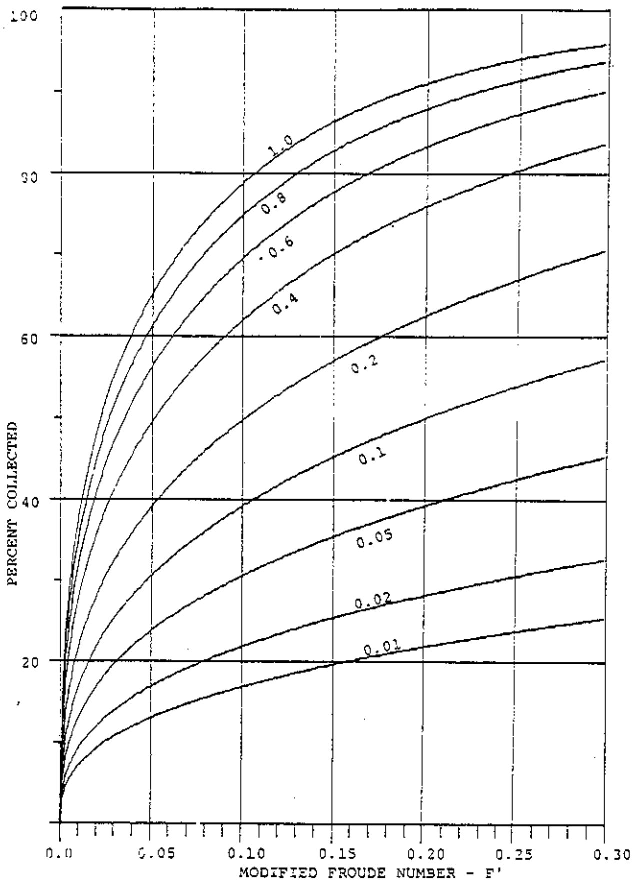

Figure 9. Percent oil collected vs. modified Froude number using equation (5.9) with: $A' = 59.69$, $B' = 6.991$ and $C' = 0.3726$. The number on each curve is the modified phase ratio, R'

7. CONCLUSIONS

When the data smoothing function generated by the laboratory scale tests is applied to the single collector intermediate scale data, the standard deviation between predicted and measured percentages of blowout liquid collection is 10.9%. Inasmuch as the standard deviation between the laboratory data itself and the smooth predictions was 8.7%, it is apparent that fairly good prediction of intermediate scale results comes from the small-scale laboratory tests.

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. With these included, the standard deviation between all single collector measurements, both at laboratory and at intermediate scales, and the new smoothing function is reduced to 8.2%, which is probably representative of the overall experimental accuracy. It is anticipated that the new smoothing function as given by equations (6.5) and (6.8)–(6.10) 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 both in the laboratory and at intermediate scale. Naturally, under conditions where a single collector is efficient there is little to be gained by use of a double collector. However, under conditions where the efficiency of a single collector is rather low, very marked gains in collection efficiency are possible through use of 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. However, there are some substantive differences in the fluid mechanical details. Much more gas remains uncollected with the 'riser only' system. Thus the phase ratio in the system is higher than that calculated for a single collector operating at the same collected liquid rate and wellhead gas flow rate. Laboratory tests have shown that a small single collector that 'spills' some of the gas, but less gas than a 'riser only' system, is more efficient than either a 'riser only' system or a single collector that spills no gas. Evidently 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 in efficiency due to some of the plume passing up beside and outside of the riser.

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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 (6.9) are shown. These are for a single collector so they provide a basis for comparison of the other systems

No.	F	R	Test (%)	Predicted (%)
		Double collector		
1	0.002	7.728	74	42
2	71461.875	8.737	118	100
3	55044.949	7.500	88	100
4	0.011	8.933	30	67
5	0.010	8.159	34	34
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	29
12	0.003	0.851	36	22
13	0.012	2.539	54	54
		Single collector		
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	56	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
		Riser only		
1	0.022	11.919	99	83
2	0.023	12.355	100	84
3	88603.062	12.072	111	100
4	0.008	11.284	87	82
5	114184.125	4.457	88	100
6	0.031	4.770	75	81
7	0.014	2,183	50	53
8	0.155	4.929	80	89
9	0.073	2.132	58	87
10	36213.795	0.404	72	100
11	0.029	1.241	53	30
12	0.011	0.452	31	31
13	0.012	1.328	34	45
14	0.004	0.418	20	20

Observations of gas bubble plumes in our laboratory have shown that immediately above the wellhead, 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. Dr David Topham (private communication) has found a similar result and ascribes it to the fact 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 an interpolating function by using a modified Froude number F' in lieu of the Froude number F where:

$$F' = Q_T/[g(h-D')^5]^{1/2} \tag{6.5}$$

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

The second scale-dependent phenomenon is the ratio between the bubble size and the length scale. Since the bubble size is related to the gas-liquid surface tension, it is not scaled and therefore the ratio is much larger at laboratory scale than at intermediate scale. Inasmuch as flow rates and physical length scales are related by Froude scaling, the length scale for this ratio can be taken as the 'air flow length', L_A, which is given by:

$$L_A = Q_A^{0.4}/g^{0.2} \tag{6.6}$$

where Q_A is the gas volume flow rate at the collector entrance. Since the scale-dependent effect of bubble size is probably most strongly related to the sizes of the largest bubbles, we will take the appropriate 'bubble length scale', L_B, as that given for a balance between surface tension and buoyancy forces for which:

$$L_B = \sqrt{\frac{T}{\rho_w g}} \tag{6.7}$$

where T is the gas-liquid surface tension (taken here as 0.072 Newtons/m) and ρ_w is the mass density of water (taken here as 1000 kg/m^3).

An increase in the amount of gas (a lower phase ratio) reduces oil collection efficiency as is described in Part I. 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 in the new interpolating function by replacing the phase ratio R with a modified phase ratio R' given by:

$$R' = R\left(1 + E'\frac{L_B}{L_A}\right) \tag{6.8}$$

The dimensionless constant E' is to be determined so that the best fit between all of the data and the interpolating function is obtained.

The new interpolating function was taken as the same form as for Part I, except for the use of the modified Froude number and phase ratio. Thus the new functional form is:

$$P = 100 \times \left[1 - \exp\left(\frac{-A' \times R' \times F'}{B' + R'}\right)\right]^{C'} \tag{6.9}$$

where P is the percentage of blowout liquid collected and the constants A', B', C', D' and E' are to be determined. As was done in Part I this was done through use of the nonlinear fitting procedure (NLIN) of the computer based Statistical Analysis System.[2] It was applied here to a data set constructed of all of the laboratory data appearing in Appendix A of Part I augmented by the data from the 16 operating conditions tested with the intermediate scale single collector. Inasmuch as the laboratory data is comprised of 62 operating conditions, the weighting of the laboratory data as compared to the intermediate scale data would be especially heavy in the function fitting procedure if only 16 intermediate scale data points were used. Therefore, the data for each of the 16 operating conditions was entered into the data set twice so that the weighting on the intermediate scale data, as compared to the laboratory scale data, is in the ratio of 32 to 62 instead of only 16 to 62.