Experiments with scale models of oil collectors for subsea well blowouts

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Laboratory experiments on conically shaped oil collectors beneath a marine riser are described. The collection concept involves oil, water and gas entering the collector and being driven into a separating sytem by gas-lift. A parametric study involving various collector shapes, heights above the wellhead, and gas, oil and water flow rates was carried out. The important dimensionless variables were identified and quantified with the conclusion that effective collection is possible if the collector height is sufficiently small and the ratio of water pumped to gas flow is sufficiently large. Increased collector heights can be accommodated at the expense of requiring increased water flows by use of larger diameter risers. The amount of gas required for most efficient oil collection is found to be much less than is expected to come from most blowouts when a single collector and riser system is used. This difficulty can be greatly diminished by the use of a specially designed gas-separating collector which passes most of the gas to the surface through a riser separate from the one which carries the liquids.

1. INTRODUCTION

The concept of installing an oil collector immediately above a subsea blowout has been considered for a long time. The most ambitious implementation of such a collecting device at sea was carried out at the IXTOC blowout during the fall of 1979. Figure 1 shows a photograph of the collecting device used at IXTOC. Oil, gas and water entered the conical collector above the wellhead and were carried by gas-lift up the sloping riser to separating equipment on the platform.

Once a blowout has occurred it is not feasible to seal a collector to the seabed around the blowout for several reasons. Even under the best of circumstances, sealing of the collector in a tight way to the bottom would be extremely difficult. In most conditions, there is a certain amount of debris around the wellhead whose presence would make such sealing impossible. Therefore, plans for emergency response to a blowout would generally be based on having the collector some distance above the seabed.

This paper presents the results of a laboratory study of subsurface collectors above the bottom. Different collector sizes and shapes were tested. With each collector, various oil flow rates, gas glow rates and riser resistances were tested. The influential factors on performance have been identified with the conclusion that effective subsurface collection with a collector above the wellhead can indeed be achieved.

We have found that under most circumstances the amount of gas coming from a well will be more than the amount required for most efficient collector operations. The fraction of escaping oil which is collected is diminished as the gas flow is increased to values above the optimum. To overcome this difficulty, we have devised a collector which separates the gas from the liquid in such a way that the performance is not degraded by increasing the gas flow rate from its optimum value. Although a comprehensive series of experiments on simple (non-separating) collectors was carried out and reported here, only preliminary tests with a separating collector have been conducted to date. These preliminary tests, which are described in Appendix B, are sufficient to demonstrate the complete feasibility of a separating collector. We plan to more fully explore the

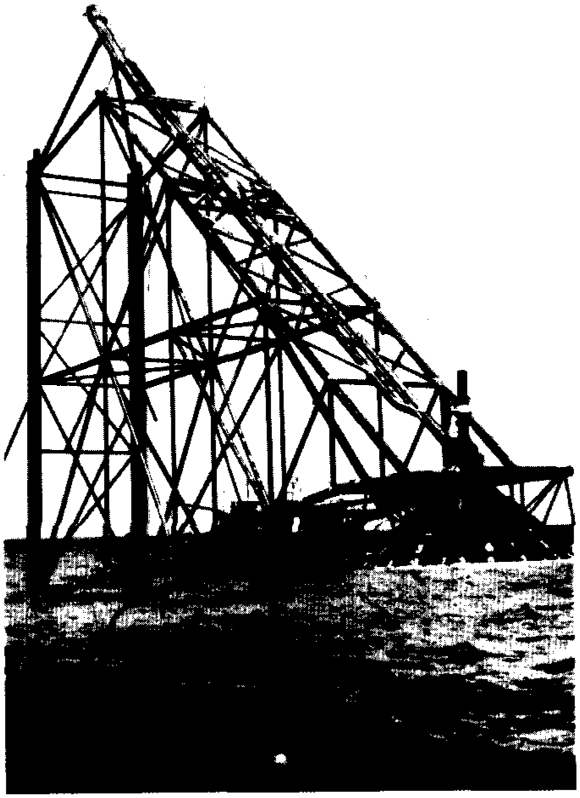

Figure 1. Photograph of full scale collector used at the IXTOC oil well blowout

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nature of the operation of separating collectors through more experiments in the future.

2. TEST APPARATUS AND MATERIALS

Tests were carried out in a tall cylindrical tank whose dimensions are shown in Fig. 2. This tank was built especially for the study of two problems related to undersea oil well blowouts: the fluid mechanical structure of rising gas plumes and the behavior of subsurface oil collectors. It is 3.96 m tall and 1.65 m in diameter with two rows of portholes diametrically opposite each other to allow observations. Adjacent to this tank in the laboratory is a large rectangular storage tank equipped with oil skimming devices. This tank was used for several purposes; storage of water from the plume tank, a dump for the water and oil collected by the collectors and recovery of the test oil from the water.

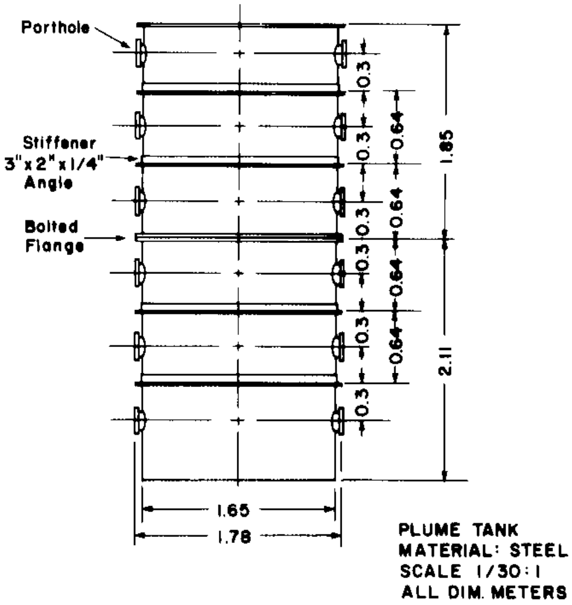

Figure 2. Drawing of the plume tank

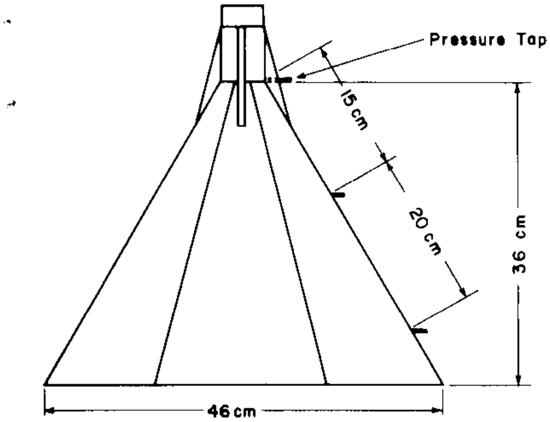

Figure 3(a). Collector number 1

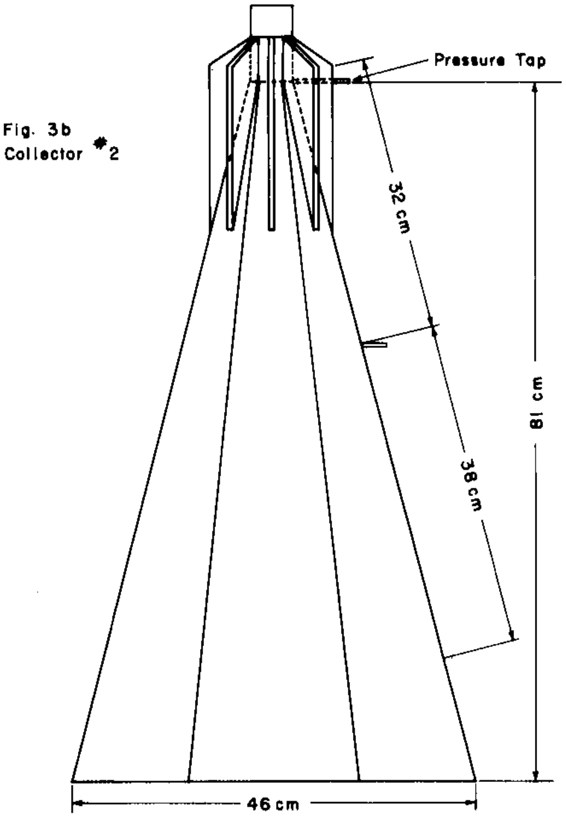

Figure 3(b). Collector number 2

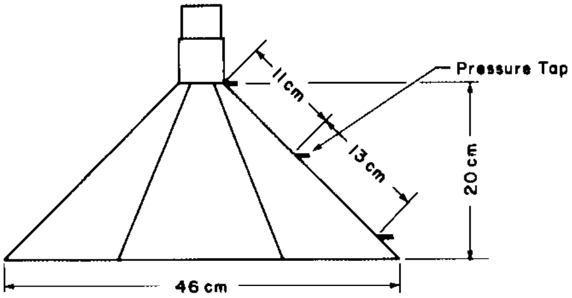

Figure 3(c). Collector number 3

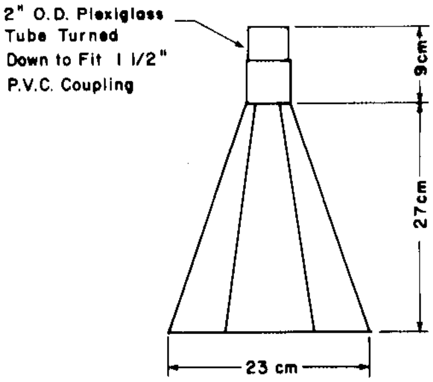

Figure 3(d). Collector number 4

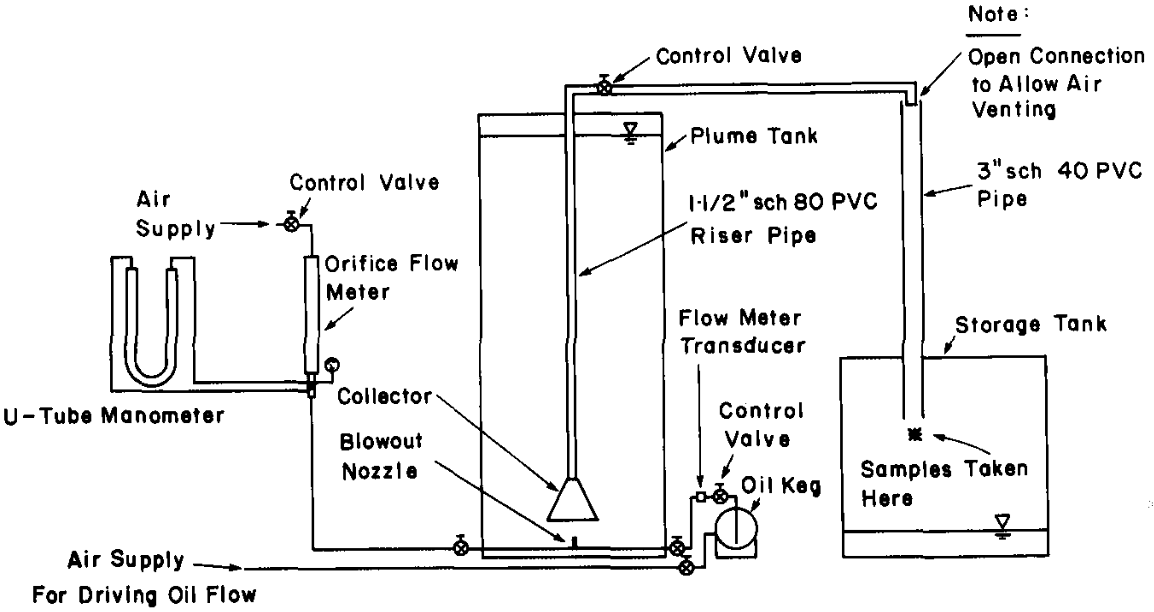

Fig. 4. Schematic arrangement of experimental apparatus

Collectors were of the inverted funnel type and were built to approximately one-fifteenth of the expected full scale. A total of five collectors were tested. Four were single-cone open-bottom collectors designed to be placed above the blowout, and one was a gas-separating collector.

All of the collectors were of octagonal cross-section and were built from $\frac{1}{4}$ in. plexiglass (the plexiglass allowed for easy construction and observation of flow patterns inside the collectors). Drawings of the single-cone collectors are shown in Fig. 3. The collectors were assigned the following names:

number 1 – standard collector
number 2 – tall collector
number 3 – flat collector
number 4 – small collector

The riser used between each collector and the surface was made of $1\frac{1}{2}$ in. schedule 80 PVC pipe (3.38 cm I.D.). It was connected to the collectors at the peak of the collector funnel and rose vertically for 3.048 m. A horizontal run of the same pipe 2.085 m long carried the flow over to the storage tank. In order to prevent siphoning action, the riser pipe dumped into the open top of a 3 in. schedule 40 PVC pipe (7.7 cm I.D.) that led vertically down to the storage tank (see Fig. 4).

Since it was necessary to run tests at a number of riser resistances, a valve was placed in the horizontal portion of the riser. Some independent experiments were run with a smaller riser ($\frac{3}{4}$ in. schedule 40 PVC pipe, 2.09 cm I.D.) to determine the effect of riser size. Results demonstrated that riser diameter only affected riser resistance and the increased riser resistance could be duplicated by using a valve on the larger riser.

Data were taken by sampling the discharge of the vertical 3 in. PVC pipe (see Fig. 4). Samples were taken using 4000 ml calibrated plastic beakers and a stop watch to time the filling of the beakers so that collected flow rates could be determined. Analysis of the samples was accomplished using 4000 ml separatory funnels to separate oil from water with subsequent volumetric measurement of each liquid.

The blowout itself was simulated by supplying air and oil to a $\frac{3}{4}$ in. pipe 'T' at the bottom of the test tank. The blowout nozzle was simply a pipe nipple screwed into the free arm of the 'T'. This allowed for easy nozzle size changes. Three separate nozzles were tested, with inside diameters of 0.925, 1.58, and 2.093 cm. Air was supplied from compressor-filled air storage tanks through an orifice flow meter. Oil was supplied from a pressurised keg. The keg is shown schematically in Fig. 5. For the experiments it was filled with approximately $0.057\ m^3$ of oil and was pressurised with air to $275.8\ kn/m^2$. The high pressure ensured that the oil flow rate would be unaffected by the comparatively small pressure variations at the blowout nozzle. The oil flow rate was measured with a turbine flow meter that had been calibrated using the test oil.

The oil used in the experiments was Drakol 7 mineral oil dyed red. Mineral oil was chosen for several reasons: it presented no fire hazard; it did not present a serious pollution problem in the event of an accident; and, being a pure hydrocarbon, it did not form stable emulsions with

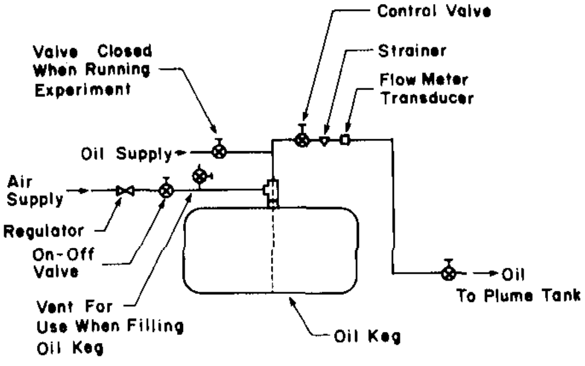

Fig. 5. Schematic drawing of the oil supply keg

the water. No attempt was made to scale interfacial tensions. Full scale measurements at IXTOC and preliminary laboratory experiments in our laboratory showed that wellhead turbulence divided the oil into small droplets (diameters much smaller than 1 mm) and that collection system water flow greatly exceeds oil flow. Under these conditions the oil flows as a 'tracer' for the moving water so that the fraction of blowout oil that is collected is not affected by the droplet dynamics which are influenced by interfacial tensions.

3. TEST PROCEDURES

In the testing of the inverted funnel collectors, seven quantities were varied: collector type, blowout air flow rate, blowout oil flow rate, riser resistance, collector height above nozzle, nozzle size and the horizontal position of the collector with respect to the nozzle (off-center position). The single dependent variable considered was the percentage of the blowout oil flow collected. The following paragraphs describe the tests conducted on each collector and the procedures used to acquire the data points.

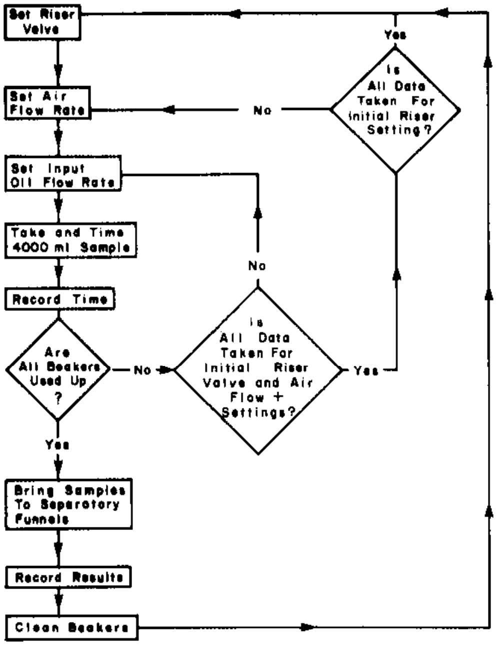

Figure 6. Flow chart showing test procedure

Figure 6 is a flow chart of the experimental procedure. The first step in putting a collector into operation was the establishment of the desired air flow rate. The gas-lift would then begin with the collected air escaping into the laboratory and the collected water coming down the collection pipe as shown in Fig. 4. Next, the desired oil flow rate was established. It was apparent when collected oil began coming down the collection pipe because of the red color of the dyed oil. Then several seconds were allowed to pass in order for steady conditions to become established in the collection system, after which a sample was taken by partially filling a 4000 ml beaker with the water and oil coming down the collection pipe while the time taken for this to occur was measured. This sample was then poured into a separatory funnel and the oil and water were allowed to separate. This took a few minutes, after which the water was drained out of the separatory funnel and the water volume was measured and then the oil was drained out and its volume was measured. Water and oil volume flow rates were established by dividing these volumes by the sample collection time. The fraction of blowout oil collected was determined as the quotient of the collected oil volume divided by the product of the input oil flow rate and the sample collection time. Five hundred and one experiments of this type were done with the single cone collectors encompassing all four collectors and a variety of oil flow rates, air flow rates, nozzle sizes, collector heights and riser resistances. Table 1 shows the flow rates and collector heights tested with each collector in the on-center location. In addition, several tests of the same type were conducted with the number one (standard) collector in off-center locations.

In running these experiments two problems were encountered. Back pressure from the oil keg caused a reduction in the set air flow rate which increased with increasing oil flow; and in transferring the samples from beaker to separatory funnel, to beaker and graduated cylinder, an indeterminate amount of oil was left on the surfaces of each container. The first gas flow effect was negligible for the larger outlet nozzles, but was noticeable for the majority of the tests which were run using the 0.925 cm nozzle. In order to be able to account for this in the analysis, an independent set of experiments was run at each air flow rate and oil flow rate and the true air flow rate was

Table 1. Tabulation of the experiments conducted on subsurface oil collectors. For each collector number, air flow rate, collector height, and oil flow rate three riser resistances were used

		Air flow rates ($\times 10^3$ m^3/s)						Oil flow rates at each air flow rate ($\times 10^6$ m^3/s)				
Collector number	Collector height (m)	1	2	3	5	7	9	31.6	63.1	94.6	126	158
1	0.178	x	x	x	x	x	x	x	x	x	x	x
	0.305	x			x		x	x	x	x	x	x
	0.530	x			x		x	x	x	x	x	x
2	0.178	x			x		x	x	x	x	x	x
3	0.178	x	x	x	x	x	x	x	x	x	x	x
4	0.076	x			x		x	x		x		x
	0.178	x			x		x	x	x	x	x	x
	0.305	x			x		x	x		x		x

recorded. The second problem of oil coated surfaces was considered to be self-curing. After one set of tests everything was coated with oil, and as subsequent tests were run, this coat of oil seemed to remain constant.

4. EXPERIMENTAL OBSERVATIONS

A complete tabulation of all of the experimental data can be found in Reference 1. One of the most obvious features of these data is that the fraction of oil collected is independent of the blowout oil flow rate when other variables are held fixed. Therefore, by considering the dependent variable to be the fraction of total oil collected, the situation is simplified by eliminating the blowout oil flow rate as an important independent variable. For each group of data (of three, four, five or six experiments), the geometry was held fixed and a nominal airflow rate was set. Then several total oil flow rates were tested. In order to eliminate total oil flow rate as a variable and to treat the small differences in other quantities properly, in each group of three, four, five or six points for which only the nominal oil flow rate was varied, the air flow rates, total collected flow rates, and fraction of oil collected were averaged. This preliminary data reduction reduces the number of cases for the open-bottom single-cone collectors to 96 sets of averages. These are tabulated in Appendix A.

Figure 7 shows curves of percentage of total oil collected versus total liquid collection rate for each nominal air flow rate for each of the collectors using the averaged data for a collector height above the nozzle of 0.178 m.* This figure demonstrates very clearly that the most important independent variables can be viewed as air flow rate and total liquid flow rate into the collector. For other experimental conditions held fixed, the total collected flow rate is determined by riser resistance.

With reference to Fig. 7(a), the data for air flow rates of 0.001, 0.002, and 0.003 m^3/s as well as the data for 0.005 and 0.007 m^3/s for high total collected flow rates follow a clear trend. The high total collected flow rates occur for low riser resistances obtained with the riser valve fully open. In each case, the data for lower total collected flow rates are obtained with more riser resistance resulting from a partially closed riser valve. As is demonstrated by the lowest total collected flow rates for the 0.005 and 0.007 m^3/s cases in Fig. 7(a), the clear trend in the data does not hold when the air flow rate becomes large and the total collected flow rate becomes small (high riser resistance). This is shown especially strongly in Fig. 7(a) for the air flow rate of 0.009 m^3/s where none of the data obeys the otherwise clear trend. Violation of the clear trend occurs because some of the air escapes outside the bottom of the collector.

Figure 8 shows a photograph of the standard collector at a height of 0.178 m above the wellhead at an air flow rate of 0.002 m^3/s and with the riser valve fully open. The outstanding feature of the internal flow in the collector is the interface between two flow regimes. Above the interface a continuous gas phase containing liquid drops exists. Below the interface liquid forms the continuous phase which contains gas bubbles. The presence of these regimes is a critical factor in collector performance. When the air flow rate is increased or when the riser resistance is increased, the liquid fraction in the upper zone is reduced and also the interface moves downward. This reduces the collected liquid flow rate for the following reasons. As the interface moves downward it becomes more difficult for liquid droplets to splash through the gas zone and reach the riser inlet. Secondly, for a gas lift pump there is an opti-

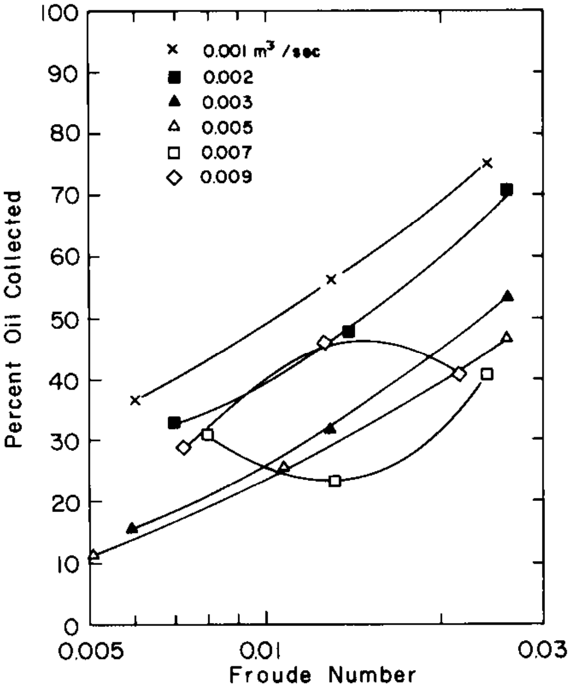

Figure 7(a). Plot of percentage oil collected versus Froude number; collector number 1

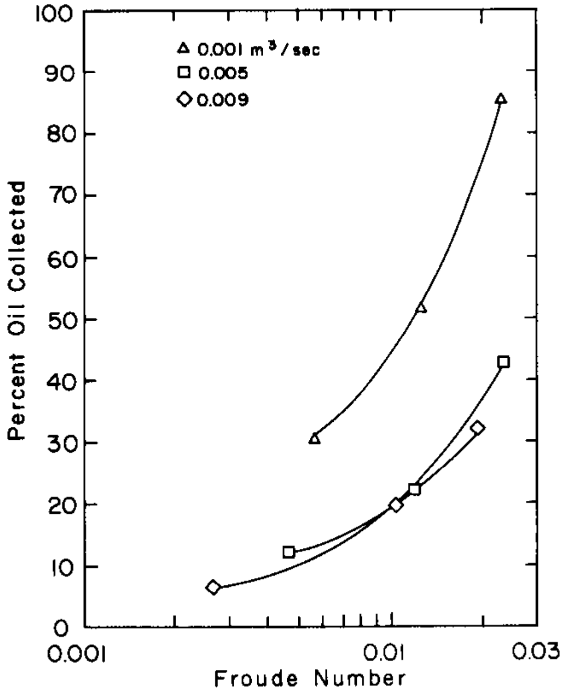

Figure 7(b). Plot of percentage oil collector versus Froude number; collector number 2

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* The Froude number is defined in Table 4. For the plots in Fig. 7 the collector height was held fixed so they are plots of percentage oil collected versus total collected flow rate.

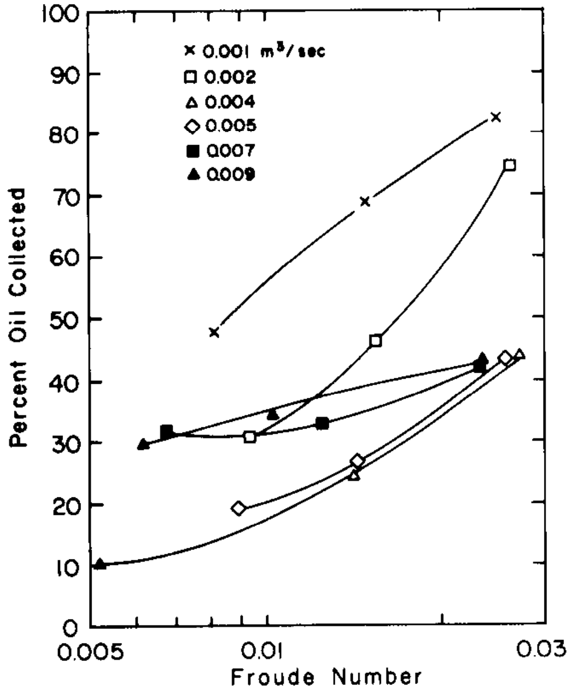

Figure 7(c). Plot of percentage oil collected versus Froude number; collector number 3

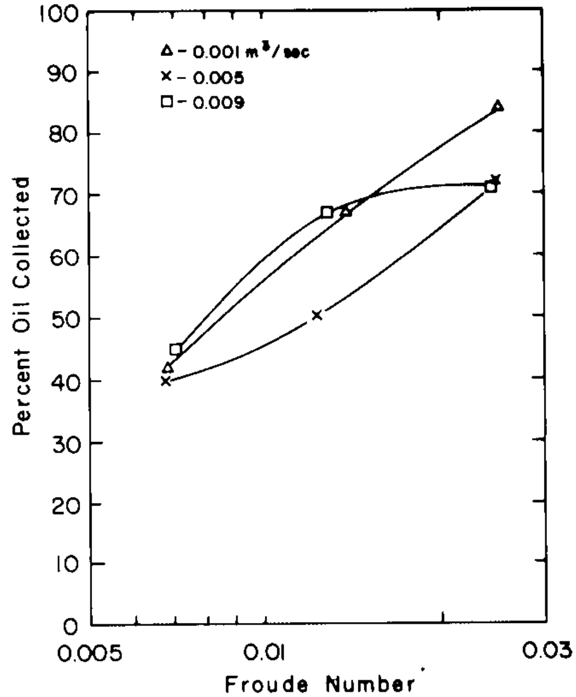

Figure 7(d). Plot of percentage oil collected versus Froude number; collector number 4

mum amount of gas flow above which more gas reduces liquid pumping. For even the lowest gas flow rate tested, more than the optimum amount of gas is supplied to the riser for gas-lift pumping. A result found in all of the data is that the percentage of blowout oil collected is increased by increased liquid pumping. Therefore, as the air flow rate is increased, the efficiency of the collector-riser system is decreased. Thirdly, the interface is an extremely turbulent region of the flow. When the interface moves closer to the bottom of the collector, this turbulence rejects more oil below and outside the collector.

Figure 7(b) is for the tall collector which did not reject air for any of the experimental conditions with the result that all of the data follow the clear trend. The data for Fig. 7(c) is for a flat collector which rejected air more easily than the so-called standard collector of Fig. 7(a) so that for Fig. 7(c) more of the data fail to follow the trend that occurs when air does not escape outside the collector bottom. Figure 7(d), which shows the data for the small collector, is particularly interesting. This small collector rejects the most air of all the collectors for high air flow rates and as a result, under these conditions the small collector collects a much higher fraction of the total escaping oil than does any other one of the single-cone open-bottom collectors. Furthermore, even at conditions for which air was not rejected, the small collector collects a somewhat higher fraction of the escaping oil than the other collectors operating at similar conditions. Hence, the collector diameter is influential on performance, but not as important as the air and liquid flow rates.

The above discussion has left out the results of the tests on the standard collector in the off-center positions. The data for these cases are tabulated in Table 2. It is seen that except in the case of the lowest riser resistance, the off-center position of one-half radius and three-quarters radius offset did not affect the percentage oil collected. In the case of low riser resistance, the difference is small. This indicates that the collector need not be directly centered over the wellhead. When the test at a full radius offset was run, oscillation of the collector makes it impossible to collect data, and no conclusions can be drawn about this extreme case of off-center position.

5. DIMENSIONAL ANALYSIS

From the standpoint of dimensional analysis, there are 19 relevant physical independent variables, as shown in Table 3. (Riser resistance is accounted for through the various flow rates.) The important dependent variable, both

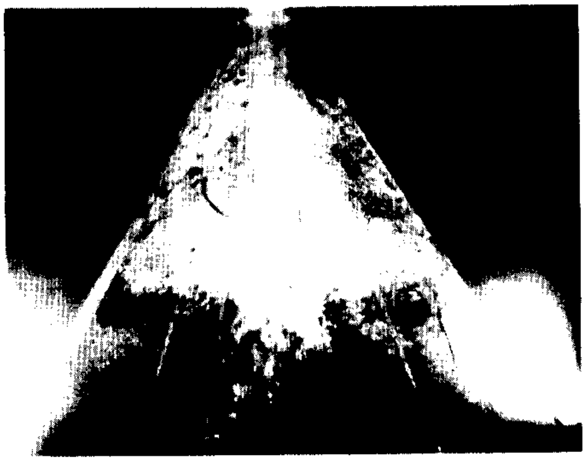

Figure 8. Photograph of operating collector, no oil present, air flow rate = 0.002 m³/s, collector height = 0.178 m.

Table 2(a). Data for off center position of the standard collector. Riser values setting – full open; air flow rate – 0.005 m^3/s; collector height – 0.178 m

Collector position	Blowout oil flow rate ($\times 10^{-6}\ m^3/s$)	Total collected flow rate ($\times 10^{-6}\ m^3/s$)	% Oil collected
Centered	31.6	1120	44
	63.1	1140	46
	94.6	1020	46
	126	1060	46
	158	1100	52
One-half radius off center	31.6	959	31
	63.1	952	34
	94.6	871	36
	126	978	35
	158	1000	35
Three-quarter radius off center	31.6	1100	25
	94.6	1070	33
	158	1100	34

Table 2(b). Riser valve setting five turns closed. Air flow rate – 0.005 m^3S; collector height – 0.178m

Collector position	Blowout oil flow rate ($\times 10^{-6}\ m^3/s$)	Total collected flow rate ($\times 10^{-6}\ m^3/s$)	% Oil collected
Centered	31.6	549	22
	63.1	574	22
	94.6	574	28
	126	568	29
	158	562	27
One-half radius off center	31.6	505	18
	63.1	562	20
	94.6	517	19
	126	479	19
	158	530	19
Three-quarter radius off center	31.6	562	15
	94.6	574	20
	158	618	23

Table 2(c). Riser valve setting 5⅔ turns closed. Air flow rate – 0.005 m^3/s; collector height – 0.178 m

Collector position	Blowout oil flow rate ($\times 10^{-6}\ m^3/s$)	Total collected flow rate ($\times 10^{-6}\ m^3/s$)	% Oil collected
Centered	31.6	183	8
	63.1	215	8
	94.6	208	11
	126	208	12
	158	254	18
One-half radius off center	31.6	303	12
	63.1	315	11
	94.6	322	11.5
	126	334	13
	158	303	18.7
Three-quarter radius off center	31.6	297	11
	94.6	303	11
	158	347	13

for an actual blowout collection operation and for our experiments, is the percentage of escaping oil that is collected.

The 19 independent variables can be combined into 16 independent dimensionless groups, which is obviously too many for efficient analysis of an experiment of the type described here. However, our experimental results show that most of these groups can be dismissed from a list of important influential groups.

For example, our results show that the volume flow rate of escaping oil (Q_0) had no significant influence on the fraction collected. Therefore, the escaping oil flow rate can be eliminated from the list of important independent variables.

Further simplification of the analysis is obtained by elimination of all Reynolds and Weber numbers from the list of influential dimensionless variables. To justify this, viscous and surface tension effects have to be considered both at the wellhead and in the plume which interacts with the collector. Three nozzle diameters were tested; having inside diameters of 0.925, 1.58, and 2.093 cm. The same collector (number 1) was used for this sequence of tests. The effects of nozzle diameter variables were found to be very small and with no significant trend. However, the nozzle diameter changes make rather large variations in the wellhead Reynolds and Weber numbers. These results indicate the insensitivity of the fraction collected to these parameters.

The major effect of viscosity and surface tensions within the highly turbulent plume and in the collector must be upon the length scales of the smallest gas bubble and oil droplet sizes. Observation of the flow shows that much of the gas is in the form of large bubbles, and it is the buoyancy and turbulence associated with these large bubbles that dominate the flow. The oil is rapidly divided into small droplets which follow the motion of the surrounding water. Hence the quantity of oil going into the collector and the riser cannot be significantly influenced by the Reynolds or Weber numbers. The size of the oil droplets is affected by these parameters which are not the same in the model as in the full-scale device. As a result, emulsion properties such as breaking time are not scaled between model tests and full scale. Nevertheless, the fraction of oil collected can be expected to be independent of Reynolds and Weber numbers and thus be properly scaled between model tests and full scale collectors.

Table 3.

Independent variables	
d	diameter of outlet nozzle (well bore)
D	diameter of base of collector
g	acceleration of gravity
h	vertical distance from nozzle (blowout) outlet to base of collector
q_g	gas volume flow rate at nozzle (blowout)
Q_o	oil volume flow rate at nozzle
Q_c	volume flow rate of collected oil
Q_w	volume flow rate of collected water
Q_T	total collected liquid flow rate ($= Q_c + Q_w$)
s	vertical height of collector (base to riser connection)
T_{og}	oil–gas interfacial tension
T_{ow}	oil–water interfacial tension
T_{wg}	water–gas interfacial tension
ρ_g	gas (mass) density
ρ_o	oil density
ρ_w	water density
ν_g	kinematic viscosity of the gas
ν_o	kinematic viscosity of the oil
ν_w	kinematic viscosity of the water
Dependent variable	
P	percentage of escaping oil that is collected

Under the conditions described above, the list of important dimensionless independent variables is reduced to the four dimensionless groups shown in Table 4.

6. DATA ANALYSIS

The preliminary observations of the data desribed previously show that the collection efficiency (fraction collected) is highly dependent on the total collected flow rate, whose increase generally increases efficiency, and on the gas flow rate, whose increase decreases collection efficiency. This indicates that both the Froude number and the Phase Ratio (see Table 1) are of major importance in determining the fraction of escaping oil that is collected. The Froude number effect is particularly clear in Fig. 9 which is a graph of percentage collected versus Froude number for collector number 4 over an especially wide range of Froude numbers. The data for this figure were obtained by operating collector number 4 not only at various riser resistances, but also over a wide range of heights so that a wide range of Froude numbers was obtained. A nominal air flow rate of 0.005 m^3/s was maintained for all of these experiments.

Table 4. Important dimensionless groups

$F = \frac{Q_T}{gh^5}$	Froude number
$R = \frac{Q_T}{q_g}$	Phase ratio
$E = \frac{D}{h}$	Enclosure ratio
$S = \frac{s}{D}$	Shape factor

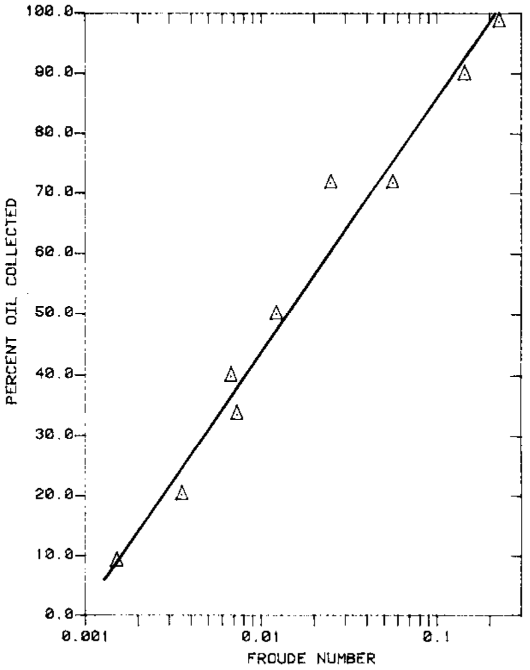

Figure 9. Percentage oil collected versus Froude number. Collector number 4. Air flow rate = 0.005 m^3/s.

Further examination of the preliminary observations of the data show that for a given height of the collector base above the nozzle (blowout point) and for a given air flow rate and a given total collected flow rate, the fractions collected are nearly the same for all collectors 1, 2 and 3 unless gas is escaping outside the bottom of a collector. Therefore, if all of the escaping gas is collected, the shape factor is not of major importance.

For any tested air and water flow rates, and for a distance from collector base to nozzle outlet (h) of 0.178 m, collector number 4 (the smallest one tested) was superior to the others as regards collection efficiency. This superior performance is especially marked at high gas flow rates. The reason for this is that at the high gas flow rates more gas escapes below and beside the small collector than the others. It was observed previously that high gas flow rates decrease the percentage of oil collected. Since collector number 4 showed superiority over the others when it loses the most gas (as observed by viewing the flow through the tank observation ports) we know that at least some of the degradation of collection efficiency by excess gas results from the gas in the collection system itself. The superior, although less marked, performance of the small collector over the others in conditions where all of the gas was collected did not occur at the collector height of 0.3048 m. Tests were done with collectors numbers 1 and 4 at this height with an air flow rate of 0.005 m^3/s for which nearly all the gas was collected. The performances of the two collectors were about equal.

To learn more about the enclosure ratio effect, we carried out a limited number of tests using the riser alone without any collector and with the open bottom end of the riser 0.178 m above the 0.925 cm diameter nozzle which simulated the wellhead. These tests were done with an air flow rate of 0.005 m^3/s and with varying oil flow rates and Froude numbers (varied by varying the riser resistance). The results were fractions collected of 0.36 and 0.31 for Froude numbers of 0.026 and 0.015 respectively. Although these results are nearly identical to those for collectors 1, 2, and 3, a direct quantitative comparison cannot be made because the collectors collected nearly all the gas in these conditions whereas the riser alone did not. However, these data are helpful in two important ways.

First, they indicate the basis for the salient effects of enclosure ratio. One involves the effect of the velocity ratio, $Q_T/\sqrt{gD^5}$, which is given by $F/(E^{0.4})$. When this quantity is large, the entrance velocity to the collector is large, which helps to draw in the surrounding liquid. Furthermore, the loss of oil from inside the collector to the outside is dominated by the high turbulence level inside the collector which is most vigorous at the interface between the bubble zone and the mist zone. When the collector diameter is increased, both the area of the interface and the volume of the turbulent zone are increased. This, coupled with the decrease in entrance velocity associated with a diameter increase must necessarily result in an increase in oil rejection from inside to outside. Another effect is that of the enclosure itself. When the collector diameter is too small in comparison to the plume diameter, some oil passes right by the collector and collection efficiency suffers as in the case of the riser alone for a height of 0.178 m and the small collector for a height of 0.3048 m. Evidently, the small collector was large enough for a height of 0.178 m for its larger entrance velocity, as compared to the larger collectors, to result in superior performance.

Second, these data show that although the influences of enclosure ratio are of some importance, they are minor in comparison to those of Froude number and phase ratio. Because of this, as well as the fact that not enough collector diameters were tested to be able to carefully quantify the effect of enclosure ratio, this parameter is not included in the subsequent analysis. Thus, the following results must be considered as 'averages' over the practical range of enclosure ratios.

For the set of conditions where all (or nearly all) of the escaping air is collected, the most important dimensionless independent variables are clearly the Froude number and the phase ratio. Symbolically, the collection efficiency can be written as:

$$P \simeq f(F, R) \qquad (1)$$

where f is a function to be determined.

Maximum engineering utility of the experimental measurements is provided by determining an approximte functional form for the relationship described in equation (1). Since this equation can be meaningful only when nearly all of the gas is collected, this functional form needs to be determined from the results of the preliminary data analysis (Appendix A) with the data for 0.007 and 0.009 m^3/s excluded because of significant escape of the air from below and beside the collectors which occurred at these flow rates in many instances.

By examination of the data and by several numerical tests, a suitable functional form for equation (1) was determined as:

$$P = 100 \times \left[1 - \exp\left(-\frac{A \times R \times F}{B + R}\right)\right]^{C} \qquad (2)$$

where A, B and C are constants to be determined.

Evaluation of the constants A, B and C was accomplished through use of the computer-based Statistical Analysis System.[2] The data used as input to the SAS system was that given in Appendix A with the exclusion of the nominal air flow rates of 0.007 and 0.009 m^3/s as discussed above.

The values obtained for the constants are:

$$A = 77.0311 \quad B = 1.41879 \quad C = 0.42753 \qquad (3a,b,c)$$

The resulting estimates at the 62 cases in Appendix A that were used have a standard deviation in percentage collected of 8.7%.

Equation (2) is intended as a smoothing and interpolating function. We have used it to generate smoothed curves of fraction collected versus Froude number for various phase ratios. These are shown in Fig. 10.

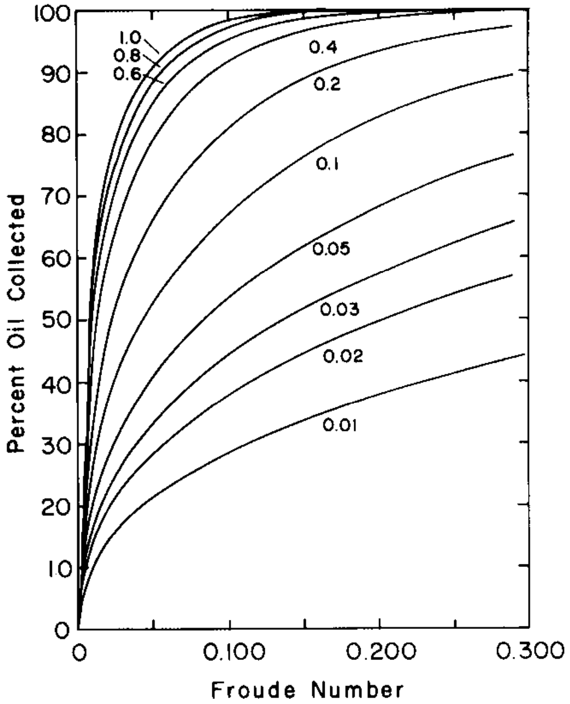

Figure 10. Percentage oil collected versus Froude number using equation (2). The number on each curve is the phase ratio, R

7. CONCLUSIONS

The experiments conducted on inverted funnel oil collectors have indicated that the three major factors affecting the percentage of blowout oil collected are riser resistance, collector height above the blowout and quantity of gas in the riser. The relationship between these three factors and the percentage oil collected is shown using two non-dimensional parameters: the Froude number based on total collected flow rate and collector height, and the phase ratio which is the ratio of liquid flow rate to gas flow rate in the riser. Plots of Froude number versus percentage oil collected at different air flow rates demonstrate that for high oil collection percentages it is necessary to have high Froude numbers and high phase ratios. The high Froude numbers correspond to a collector which is close to the blowout and pumping large quantities of oil and water (i.e. the riser resistance is low). The high phase ratios correspond to situations where there is relatively little gas in the rsier and a relatively high interface in the collector; a situation that allows the gas lift in the riser and the liquid passage in the collector to operate efficiency.

A function relating percentage oil collected to Froude number and gas fraction has been fitted to the data and is presented. A plot of this function clearly demonstrates the importance of these two variables.

In summary, there are three critical factors to be considered in the design of an inverted funnel subsurface oil collector. They are blowout gas flow rate, riser resistance, and height of the collector above the blowout. To achieve high blowout oil collection percentages it is necessary to have a riser with low resistance and a collector as close to the blowouts as possible. The results show very clearly that if the resulting Froude number and phase ratio are high enough, very efficient oil collection can be achieved. The lower the phase ratio, the higher is the required Froude number for efficient collection.

Under many blowout circumstances it is impossible to achieve a high enough phase ratio for efficient collection unless the riser diameter is impractically large. For such circumstances the gas-separating collector described in Appendix B is a most promising device for achieving efficient collection.

REFERENCES

1 Burgess, J. Subsurface collectors for undersea oil well blowouts, Masters Thesis, MIT Department of Ocean Engineering, 1981
2 Helwig, Jane T. (ed.). *SAS Users Guide*, SAS Institute Inc., 1979

APPENDIX A

Reduced data set from experiments on subsurface oil collectors

FILE: CNVT DATA A VM/SP CONVERSATIONAL MONITOR SYSTEM

CNBR	HEIGHT	JETDIA	AIRFLO	OILFLO	OILCOLR	TOTCOLR	PEROIL
1	0.178	0.925	0.001	0.0001	0.5820E-04	0.9885E-03	77.7
1	0.178	0.925	0.001	0.0001	0.5982E-04	0.5255E-03	57.7
1	0.178	0.925	0.001	0.0001	0.4093E-04	0.2460E-03	33.5
1	0.178	0.925	0.002	0.0001	0.6282E-04	0.1078E-02	70.1
1	0.178	0.925	0.002	0.0001	0.5190E-04	0.5520E-03	49.7
1	0.178	0.925	0.002	0.0001	0.3390E-04	0.2775E-03	32.9
1	0.178	0.925	0.003	0.0001	0.5640E-04	0.1062E-02	54.9
1	0.178	0.925	0.003	0.0001	0.3312E-04	0.5280E-03	30.8
1	0.178	0.925	0.003	0.0001	0.1350E-04	0.2340E-03	13.7
1	0.178	0.925	0.004	0.0001	0.5070E-04	0.1028E-02	47.6
1	0.178	0.925	0.004	0.0001	0.2862E-04	0.5415E-03	26.7
1	0.178	0.925	0.004	0.0001	0.1002E-04	0.2990E-03	10.6
1	0.178	0.925	0.006	0.0001	0.4218E-04	0.9680E-03	41.9
1	0.178	0.925	0.006	0.0001	0.2610E-04	0.5325E-03	24.1
1	0.178	0.925	0.006	0.0001	0.4650E-04	0.3870E-03	34.7
1	0.178	0.925	0.006	0.0001	0.3378E-04	0.2940E-03	28.5
1	0.178	0.925	0.008	0.0001	0.4272E-04	0.8655E-03	40.5
1	0.178	0.925	0.008	0.0001	0.5112E-04	0.5340E-03	48.2
1	0.178	0.925	0.008	0.0001	0.2982E-04	0.2970E-03	29.0
1	0.178	1.580	0.001	0.0001	0.8598E-04	0.9954E-03	71.6
1	0.178	1.580	0.001	0.0001	0.7710E-04	0.5925E-03	71.3
1	0.178	1.580	0.001	0.0001	0.4680E-04	0.3030E-03	44.4
1	0.178	2.093	0.001	0.0001	0.6138E-04	0.9140E-03	51.1
1	0.178	2.093	0.001	0.0001	0.5706E-04	0.5922E-03	46.6
1	0.178	2.093	0.001	0.0001	0.4662E-04	0.3420E-03	37.3
1	0.305	0.925	0.001	0.0001	0.5940E-04	0.8010E-03	50.3
1	0.305	0.925	0.001	0.0001	0.3900E-04	0.5170E-03	38.0
1	0.305	0.925	0.001	0.0001	0.3150E-04	0.3454E-03	32.0
1	0.533	0.925	0.001	0.0001	0.1992E-04	0.7030E-03	16.7
1	0.533	0.925	0.001	0.0001	0.1512E-04	0.5020E-03	14.6
1	0.533	0.925	0.001	0.0001	0.1344E-04	0.5034E-03	12.5
1	0.178	1.580	0.005	0.0001	0.6342E-04	0.9900E-03	53.5
1	0.178	1.580	0.005	0.0001	0.3810E-04	0.5625E-03	34.6
1	0.178	1.560	0.005	0.0001	0.1930E-04	0.2420E-03	16.2
1	0.178	2.093	0.005	0.0001	0.4726E-04	0.9420E-03	39.2
1	0.178	2.093	0.005	0.0001	0.3360E-04	0.5460E-03	26.9
1	0.178	2.093	0.005	0.0001	0.1890E-04	0.3026E-03	17.8
1	0.305	0.925	0.004	0.0001	0.2664E-04	0.9489E-03	25.5
1	0.305	0.925	0.004	0.0001	0.1644E-04	0.5190E-03	15.9
1	0.305	0.925	0.004	0.0001	0.1278E-04	0.2616E-03	10.4
1	0.533	0.925	0.004	0.0001	0.1146E-04	0.9258E-03	10.7
1	0.533	0.925	0.004	0.0001	0.7320E-05	0.5535E-03	7.1
1	0.533	0.925	0.004	0.0001	0.4740E-05	0.3123E-03	4.6
1	0.178	1.580	0.009	0.0001	0.2760E-04	0.9010E-03	25.7
1	0.178	1.580	0.009	0.0001	0.1590E-04	0.4659E-03	15.0
1	0.178	1.560	0.009	0.0001	0.6000E-05	0.1890E-03	6.3
1	0.178	2.093	0.009	0.0001	0.3198E-04	0.8418E-03	26.0
1	0.178	2.093	0.009	0.0001	0.1962E-04	0.4620E-03	16.0
1	0.178	2.093	0.009	0.0001	0.1200E-04	0.2761E-03	10.6
1	0.305	0.925	0.008	0.0001	0.3000E-04	0.9550E-03	28.3

LIST OF VARIABLES

CNBR	Collector number
HEIGHT	Collector height above nozzle (m)
JETDIA	Inside diameter of nozzle (cm)
AIRFlo	Air flow rate (m^3/s)
OILFlo	Oil flow rate (m^3/s)
OILColR	Collected oil flow rate (m^3/s)
TOTColR	Total liquid collected flow rate (m^3/s)
PERoil	Percentage blowout oil flow collected

FILE: CNVT DATA A VM/SP CONVERSATIONAL MONITOR SYSTEM

CNBR	HEIGHT	JETDIA	AIRFLO	OILFLO	OILCOLR	TOTCOLR	PEROIL
1	0.305	0.922	0.008	0.0001	0.3300E-04	0.4905E-03	28.6
1	0.305	0.925	0.008	0.0001	0.2802E-04	0.3748E-03	23.9
1	0.533	0.925	0.008	0.0001	0.9000E-05	0.8625E-03	7.9
1	0.533	0.925	0.008	0.0001	0.6900E-05	0.4521E-03	6.4
1	0.533	0.925	0.008	0.0001	0.1920E-05	0.1645E-03	1.9
2	0.178	0.925	0.001	0.0001	0.8100E-04	0.9450E-03	77.5
2	0.178	0.925	0.001	0.0001	0.4878E-04	0.5020E-03	53.6
2	0.178	0.925	0.001	0.0001	0.2772E-04	0.2265E-03	28.9
2	0.178	0.925	0.004	0.0001	0.4320E-04	0.9640E-03	44.3
2	0.178	0.925	0.004	0.0001	0.2292E-04	0.4800E-03	21.5
2	0.178	0.925	0.004	0.0001	0.1182E-04	0.1905E-03	11.5
2	0.178	0.925	0.008	0.0001	0.3540E-04	0.7860E-03	32.6
2	0.178	0.925	0.008	0.0001	0.2196E-04	0.4212E-03	19.7
2	0.178	0.925	0.008	0.0001	0.6600E-05	0.1101E-03	6.2
3	0.178	0.925	0.001	0.0001	0.1112E-03	0.1047E-02	83.0
3	0.178	0.925	0.001	0.0001	0.8088E-04	0.5994E-03	71.4
3	0.178	0.925	0.001	0.0001	0.4596E-04	0.3330E-03	44.6
3	0.178	0.925	0.002	0.0001	0.7722E-04	0.1063E-02	74.5
3	0.178	0.925	0.002	0.0001	0.5328E-04	0.6210E-03	46.5
3	0.178	0.925	0.002	0.0001	0.3612E-04	0.3739E-03	30.4
3	0.178	0.925	0.003	0.0001	0.5580E-04	0.1101E-02	45.2
3	0.178	0.925	0.003	0.0001	0.3000E-04	0.5724E-03	24.2
3	0.178	0.925	0.003	0.0001	0.1332E-04	0.2094E-03	10.4
3	0.178	0.925	0.004	0.0001	0.5436E-04	0.1048E-02	44.6
3	0.178	0.925	0.004	0.0001	0.3288E-04	0.5814E-03	27.2
3	0.178	0.925	0.004	0.0001	0.2412E-04	0.3576E-03	19.4
3	0.178	0.925	0.006	0.0001	0.4560E-04	0.9472E-03	43.4
3	0.178	0.925	0.006	0.0001	0.3522E-04	0.5040E-03	32.9
3	0.178	0.925	0.006	0.0001	0.3300E-04	0.2775E-03	31.7
3	0.178	0.925	0.009	0.0001	0.4662E-04	0.9765E-03	44.4
3	0.178	0.925	0.008	0.0001	0.3780E-04	0.4240E-03	34.1
3	0.176	0.925	0.009	0.0001	0.3090E-04	0.2535E-03	29.7
4	0.178	0.925	0.001	0.0001	0.1074E-03	0.9480E-03	79.7
4	0.178	0.925	0.001	0.0001	0.6978E-04	0.5080E-03	58.9
4	0.178	0.925	0.001	0.0001	0.3618E-04	0.2730E-03	41.3
4	0.178	0.925	0.004	0.0001	0.7542E-04	0.9931E-03	71.9
4	0.178	0.925	0.004	0.0001	0.5160E-04	0.4930E-03	50.1
4	0.178	0.925	0.004	0.0001	0.4842E-04	0.2780E-03	40.7
4	0.178	0.925	0.008	0.0001	0.7620E-04	0.9720E-03	71.6
4	0.178	0.925	0.008	0.0001	0.7182E-04	0.5211E-03	67.9
4	0.178	0.925	0.008	0.0001	0.4500E-04	0.2878E-03	46.2
4	0.076	0.925	0.004	0.0001	0.1173E-03	0.1101E-02	97.5
4	0.076	0.925	0.004	0.0001	0.1089E-03	0.7140E-03	90.2
4	0.076	0.925	0.004	0.0002	0.1086E-03	0.2940E-03	72.4
4	0.305	0.925	0.004	0.0001	0.4170E-04	0.1062E-02	35.1
4	0.305	0.925	0.004	0.0001	0.2430E-04	0.5460E-03	20.3