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SUBSEA COLLECTION OF OIL FROM A WELL BLOWOUT

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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 at the IXTOC blowout during the Fall of 1979. Figure 1 shows a photograph of the collecting device used at IXTOC. The triangular truss was supported from a platform 200 feet from the well. Oil, gas and water entered the conical collector above the wellhead and was carried by gas-lift up the sloping riser to separation 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.

The major part of this report deals with 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 flow rates and riser resistances (which affects the total liquid flow through the riser) were tested. The influential factors on performance have been identified with the conclusion that effective subsurface collection with a collector above the well head 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 operation. The fraction of escaping oil which is collected is diminished as the gas flow is increased to values above optimum. To overcome this difficulty, we have devised a collector which separates the gas from the liquid in 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, we have had only enough time to carry out preliminary tests with a separating collector. These preliminary tests, which are reported here, are sufficient to demonstrate the complete feasibility of a separating collector, but we plan to more fully explore the nature of the operation of separating collectors through more experiments in the future.

It was mentioned above that it is generally not feasible to seal to the sea bottom a collector used for emergency response to a blowout. However, it is feasible to seal a collector to the bottom before drilling begins. Such a collector, which might be installed in areas which are not acceptable for emergency reponse, such as in the arctic, would have drilling and production taking place through a special port in the top of the collector. We have carried out a series of laboratory scale tests on a "bottom mounted collector." Although these collectors were sealed to the bottom, they were not completely closed. A number of holes were located in the sides of the collector. The sizes of these holes were varied in order to learn how the amount of hole area affects various aspects of performance. One of the things which we learned was that a relatively large amount of water enters the collection system through very small holes. In addition to providing useful information about bottom-mounted collectors, this result shows the inadvisability of trying to seal an emergency response collector to the bottom. Even relatively small leaks between the collector bottom and the seabed would result in collecting almost as much water as would be the case with a collector located some distance above the seabed.

2. Apparatus and Models

The experiments were carried out in a cylindrical, open-topped tank having a height of 156" and a diameter of 65". Twelve viewing ports in the tank wall permitted observation of many of the experiments. Air and oil were delivered to a vertical 2" long section of pipe which acted as a nozzle for the simulated blowout. The ranges of the experimental flow rates were from 2.5 to 20 SCFM of gas and 0.5 to 3.0 GPM of oil. The physical sizes involved are about 1/15'th of those for actual full-scale circumstances. For Froude scaling, flow rates scale in proportion to the 5/2's power of the length so that the experimental flow rates correspond to full-scale flow rates of approximately 3 million to 25 million standard cubic feet of gas per day and 15,000 to 90,000 barrels of oil per day. The large scaled up values for the oil flow rate were used because the results for fraction of blowout oil collected were found to be insensitive to variations in oil flow rate (the oil is essentially a "tracer" in the gas-liquid plume) and the larger volumes of oil were easier to measure in our apparatus than the smaller volumes.

The inverted cone shaped collectors as shown in Fig. 2 were tested. When a collector was tested, it was located with its bottom edge a known distance above the nozzle outlet. The collected oil, gas (air) and water passed through a riser to a collecting pipe near the top of the tank with the air escaping off the top of the pipe and the water and oil being conducted down through this pipe to a collection tank. The flow was driven up the riser by gas-lift just as would be the case in a full-scale device. Independent experiments confirmed that the effect of the riser characteristics on collection were strictly related to riser resistance. For example, a small diameter riser with small lift resulted in identical collection to a large diameter riser with large lift if both had the same riser resistance. Therefore, the effect of different riser characteristics could be simulated very simply by installing a valve near the top of the riser and carrying out each experiment with different valve settings (resistances).

Each oil collection experiment was done in the following way. The collector was first put into operation by establishing the desired air flow rate. This was measured by means of an orifice meter in the air delivery system. The gas lift would begin and air escaped to the top of the room and the collected water came down the collection pipe. The arrangement is sketched in Fig. 3. Then, the desired oil flow rate, as measured by a turbine flow meter in the oil delivery line was established. The oil used for the experiments was Drakol 7 mineral oil dyed red to make it easily visible. The red color in the collection pipe outlet became apparent when the oily flow came out of the system. Several seconds were allowed to pass for steady conditions to become established. Then a sample of the liquid coming out of the collection pipe was taken. The sample size was approximately 4000 ml. and the time to collect the sample was measured. This sample was then poured into a separatory funnel where the oil and water collected were allowed to separate. The water was drained from the separatory funnel into a calibrated beaker. Then the oil was drained into a calibrated graduate. By dividing these liquid quantities by the previously measured collection time, the collected water and oil flow rates were established. The fraction of blowout oil collected was determined by dividing the volume of collected oil by the product of oil blowout flow rate and collection time. 501 experiments of this type were done encompassing a variety of different collectors, oil flow rates, air flow rates, collector heights, and riser resistances.

A concept for a collector that might be installed in vulnerable areas before drilling were to begin is sketched in Fig. 4. Initially, it was thought that if such a collector were completely sealed, the internal pressure that might be developed in the presence of a blowout would be sufficient to break any collector having an acceptable structure or to blow it right off the seabed. Therefore, we first envisioned a collector of this type with a few holes in it having sufficient total area to adequately limit the maximum internal pressure. To test the concept, a bottom-mounted collector as sketched in Fig. 5 was tested. Two kinds of experiments with this collector were done. The first type was comprised of a series of 102 tests utilizing air and water, without oil, then the differences in pressure between the inside and the outside of the collector at the three locations shown in Fig. 5 were measured. The main purpose of these tests was to establish the pressures and forces a bottom-mounted collector might encounter. Secondly, for a few of these tests oil was introduced through the nozzle along with the air for a sufficiently long period of time to determine whether or not much of the oil escaped through the holes in the sides of the collector.

For the open bottom collectors, large amounts of collected gas were found to have two derogatory effects. First of all, the fraction of total oil collected is diminished when the gas flow is increased because the increased gas flow results in a reduced water flow into the system. This occurs because maximum gas-lift pumping in anticipated riser sizes is achieved with less gas flow than generally occurs in blowouts and also in our experiments. Since increased water flow draws an increased oil flow into the system, reduced water flow decreases oil collection. Secondly, more oil is lost when the gas flow is increased due to actual rejection of some of the oil in the collector to the outside through and across the collector bottom. For typical operating conditions, there is a bubble flow zone in the bottom portion of the collector and a mist flow zone near the top with a boundary between the two zones at some height in the collector that depends on operating conditions. Near the interface, the intensity of the turbulence is particularly strong. As the gas flow rate is increased, this interface moves lower in the collector and the intensity of the turbulence increases. Both of these effects increase the rejection of oil by the internal turbulence.

To minimize the adverse effect of high gas flow rates, we devised the collector shown in Fig. 6 which separates most of the gas from the remainder of the flow. The valve on the gas riser can be closed to the point where a small amount of gas escapes from the inner gas collector to the outer liquid. This small amount of gas is closer to the optimum gas for driving the maximum possible flow in the liquid riser than the large amount of gas coming from the well. This overcomes both of the major difficulties mentioned above which are associated with large gas flow rates. Although a complete parametric series of tests for the separating collector (double collector) has not yet been carried out, we did carry out nine oil collection experiments to demonstrate the concept and its feasibility.

It should be mentioned that the pressure measurement tests, as described above for the bottom-mounted collector, were also carried out for the parametric series of simple collectors. However, these results do not relate to the main theme of this report and they are not presented here. They will subsequently be presented elsewhere.

3. Preliminary Observations of the Data:

All of the oil collection measurements for the open bottom single cone collectors are given in appendix A. The preliminary observations to be explained here were used in developing subsequent plans for analyzing these data. Before the subsequent analysis, it is useful to consider the fraction (or percent) of outflow oil collected as the dependent variable and to try to determine the effects of all other independent variables upon it.

One of the most obvious features of the data shown in appendix A is that in nearly all instances the fraction of oil collected is independent of the oil well outflow rate when other variables are held fixed. Even in those instances where there is a small dependence of fraction collected upon the oil outflow rate, the effect is relatively small in comparison to other effects on performance. Therefore, by considering the dependent variable to be the fraction of total oil collected, the situation is simplified by eliminating the total 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. Therefore, 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 reduced the number of cases for the open bottom single cone collectors to 96 sets of averages. These are tabluated in appendix B.

Figure 7 shows curves of percent 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 h=7". 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. 7A, the data for air flow rates of 2.4, 4.8, 7.1 SCFM as well as the data for 10 and 15 SCFM for high total collected flow rates follow a clear trend. The high total collected flow rates occur for low riser resistance 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 10 SCFM and 15 SCFM cases in Fig. 7A, 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. 7A for the air flow rate of 20 SCFM 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. Fig. 8 shows the appearance of the flow. When air is not lost outside the bottom of a collector, increasing either the air flow rate or the riser resistance results in a lowering of the interface in the collector between the bubble zone and the mist zone. The closer that this interface is to the bottom of a collector, the higher will be the oil rejection by the turbulent flow.

Figure 7B 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. 7C is for a flat collector which rejected air more easily than the so-called standard collector of Fig. 7A so that for Fig.7C more of the data fail to follow the trend that occurs when air does not escape outside the collector bottom. Figure 7D, 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.

4. Dimensional Analysis:

From the standpoint of dimensional analysis, there are nineteen relevant physical independent variables as shown below in Table 1 (riser resistance is accounted for throught the various flow rates). The important dependent variable, both for an actual blowout collection operation and for our experiments is the fraction of escaping oil that is collected.

Table 1

Independent Variables

d - diameter of outlet nozzle (well bore)

D - diameter of base of collector

g - accelaeration 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 - fraction of escaping oil that is collected

Important Independent Dimensionless Groups

$F = \frac{Q_T}{\sqrt{gh^5}}$, Froude Number

$R = \frac{Q_T}{q_q}$, Phase Ratio

$E = \frac{D}{h}$, Enclosure Ratio

$S = \frac{s}{D}$, Shape Factor

The nineteen independent variables can be combined into sixteen independent dimensionless groups which are obviously too many for efficient analysis of an experiment of the type described here. Most of these groups can be dismissed from a list of influential groups by an appeal to the preliminary examination of experimental results presented in the preceding section.

We know that the volume flow rate of escaping oil (Q_o) 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 0.364", 0.622" and 0.824". The same collector (#1) was used for this sequence of tests. The results show a small increase in fraction of oil collected when the 0.364" nozzle is replaced by the 0.622" nozzle. However, when the nozzle diameter is increased to 0.824" the fraction collected diminishes to a value slightly less than was obtained with the 0.364" nozzle. The effects of nozzle diameter variations are very small and show 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 tests as in a 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.

Under the conditions described above, the list of important dimensionless independent variables is reduced to the four dimensionless groups shown in Table 1.

5. Analysis of the Data for the Series of the Single Cone Open Bottom Collectors:

The preliminary observations of the data described in §3 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 determining the fraction of escaping oil that is collected. The Froude number effect is particularly clear in Fig. 9 which is a graph of fraction collected vs. Froude number for collector number 4 over an especially wide range of Froude numbers. The data for this figure were obtained by operating collector 4 not only at various riser resistances, but also over a wide range of heights so that the wide range of Froude number was obtained. A nominal air flow rate of 10 SCFM was maintained for all of these experiments.

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 collectors 1, 2 and 3 unless gas was 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 7", collector 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 collection efficiency. Since collector number 4 has more 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 for h=12". Tests were done with collectors number 1 and 4 at this height with an airflow rate of 10 SCFM 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 1.5" inside diameter riser alone without any collector and with the open bottom end of the riser 7" above the 0.364" diameter nozzle which simulated the wellhead. These tests were done with an air flow rate of 10 SCFM 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 h=7" and the small collector for h=12". Evidently, the small collector was large enough for h=7" 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

$$\Gamma \cong f(F,R) \qquad (1)$$

where f is a function to be determined.

Maximum engineering utility of the experimental measurements is provided by determining an approximate functional form for the relationship described symbolically in equation 1. Inasmuch as 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 B) with the data for 15 SCFM and 20 SCFM 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

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

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 (ref. 1). The data used as input to the SAS system was that given in appendix B with the exclusion of the nominal air flow rates of 15 SCFM and 20 SCFM because some gas escape outside some of the collectors occurred with much of those data.

The values obtained for the constants are :

A=77.0311, B=1.41879, C=0.42753 (3 a, b, c)

The resulting estimates at the 62 cases in appendix B that were used have a standard deviation in fraction collected of 0.087.

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

6. Discussion of Results for Single Cone Open Bottom Collectors:

The most important aspects of the performance of single cone open bottom collectors can be obtained from Fig. 10. In particular, for any Froude number and phase ratio a reasonably good estimate of the fraction collected (collection efficiency) can be made. To know the Froude number and phase ratio for any particular set of circumstances so that Fig 10 can be used, the total liquid collected flow rate must be estimated. Since the presence of the oil has only a minimal effect on the total collected liquid flow rate, the determination of this flow rate can be made with sufficient accuracy for water alone. There are two interrelated parts for this determination. For any specific gas flow through a specific riser there is a unique relationship between water flow rate and pressure drop. This can be determined by the methods of Brill and Beggs (ref. 2). With the top of the riser at atmospheric pressure, this gives a unique relationship between liquid flow rate and pressure at the top of the collector (bottom of the riser) for any specific collector geometry. The actual liquid flow rate that occurs is the one for which the pressure and flow conditions for both the riser and the collector are simultaneously satisfied.

Although the details of our measurements of collector flow rates vs internal collector pressures are not given here, an important generalization can be made. This is that for almost any anticipated operating condition the variation between the actual pressure at the entrance to the riser and the hydrostatic pressure at the same height is relatively small in comparison to the other pressures that determine riser operation. In actuality, the pressure at the bottom of the riser is just a bit higher than hydrostatic because of the "gas load" inside the collector. This actual driving pressure excess will be able to be estimated, in general, when we analyze and present the results of our internal pressure measurements.

Figure 10 can be viewed as an "average" over-all enclosure ratios for cases where nearly all of the gas was collected. The influence of enclósure ratio on the performance characterisitics as a function of Froude number and Phase Ratio has been "averaged out". We do know, however, that collector size does have a small influence on performance. Although we have not yet obtained sufficient data for various collector sizes to fully quantify this effect, the data we do have indicates that the collector diameter for maximum oil collection is approximately equal to the height, h, above the wellhead at which the collector is operated. Since this height must generally be rather small in order to achieve a high enough Froude number for efficient oil collection, a diameter larger than this height might well be desirable to limit the gas escape that could add danger to surface operations. However, an important result is that the optimum size for a collector on the bottom of a riser is a great deal smaller than was heretofore generally thought to be the case.

7. <u>The Bottom Mounted Collector</u>

Tests were carried out on a model of a bottom mounted collector of the type sketched in Fig. 5. The tests were of two types. First, for a variety of riser resistances, air flow rates, and hole sizes; pressures were measured at three points in the collector. There were eight holes in the sides of the collector and tests were done with hole sizes of 1/8", 1/4" and 1/2". Second, for a few combinations of air flow rates, riser resistances and hole sizes some oil was released through the nozzle (simulated well bore) and observations were made as to whether or not any of the oil came out through the holes in the side of the collector. These tests were done with clean water in the tank so that good observations through the viewing ports could be made.

The description of results for the bottom mounted collector must be prefaced with the important statement that only one bottom mounted collector was tested. Therefore, we have not learned how details of collector shape affect collection efficiency for such a device. For example, the conditions to be described for which leakage might begin to occur with this particular collector might not be the same conditions for which leakage would begin with a collector having the same diameter, but twice as tall. Furthermore, the effect of the dimensionless quantity of hole diameter divided by collector diameter cannot be evaluated because, as will subsequently be described, a different dimensionless parameter involving hole diameter was found to be very important and the results were determined in terms of this parameter instead. A variety of different collector diameters would have to be tested in order to determine the effect of the dimensionless parameter given by hole diameter divided by collector diameter. Nevertheless, a great deal has been learned about the operation of a bottom mounted collector by means of the few tests which we have been able to carry out thus far.

Appendix C shows the results of measurement of the pressure differences between the inside of the bottom mounted collector and the outside at the three different locations shown in Fig. 5. Although a detailed analysis of the relationship between flow through the holes and pressure difference has not yet been made, appendix C shows very clearly that the internal pressures are almost always less than the external pressures; this condition being indicated by a negative pressure difference. In fact, the only occurrences of positive pressure differences (more pressure inside than outside) are for the largest hole sizes and for the highest pressure measurement points.

The generally negative pressure differences mean that in operation the hydrodynamic forces tend to press the collector onto the bottom, rather than drive it off the bottom. One of the reasons for considering the use of holes in the side of a bottom mounted collector was to limit the maximum forces tending to drive the collector away from the bottom. It would be difficult to construct bottom attachments in practice that were strong enough to withstand significantly positive pressure differences. On the other hand, with negative pressure differences there is no difficulty in holding the collector on the bottom and it is quite straightforward to design and construct a collector that is strong enough to itself withstand the now generally expected negative pressure differences. What this means is that it might well be feasible to operate a bottom mounted collector without open holes through the sides of the device. Since significantly positive pressure differences could temporarily exist immediately after a blowout, but before the gas lift in the riser starts operating with a substantial amount of gas in the riser, a useful design would be one which has a valve in the side of the collector between the inside and the outside. Normal petroleum operations could take place with the valve open. If a blowout occurred, the open valve would limit the initially possible positive pressure differences. After flow in the riser was established, the valve could be closed leading to a major reduction in collected water with the result that the oil-water separators could be much smaller than would be the case in the presence of holes.

The data shows that even small holes lead to substantial water flow. For example, eight 1/2" diameter holes lead to as much water collection as an open bottom collector operating under the same conditions. Even when the 8 holes have a diameter of only 1/8", the collected water flow rate is 60% of the water flow rate for an open bottom collector operating under the same conditions. Therefore, if a bottom mounted collector without holes is used and if a small leak develops between the sea bed and the collector, the velocity through the leak will be quite high. This could well lead to scouring of the bottom with the scoured sediment coming up the riser. To avoid this, an actual device should have the capability of opening the valve from the inside to outside on the side of the device to allow water to enter through the side and thereby diminish the scouring action at the bottom.

In the tests where a small almount of oil was released with the air and the presence or absence of oil leakage through the holes was observed, we found that increasing the hole size increased the oil leakage, and that the oil leakage was diminished by increases in water flow rate or the phase ratio, R (water flow rate/gas flow rate). To put this effect in dimensionless terms, the important independent dimensionless variables need to be determined. One is obviously the phase ratio. Another is F_h, the Froude number based on total hole area. It is given by

$$F_n = \frac{Q_T}{g^{0.5}\,(nA)^{1.25}}$$

where there are n holes, each having area A.

In the tests we carried out with substantial amounts of oil, the percentage of escaping oil that was collected was found to be independent of oil flow rate; just as was the case with the open bottom collectors. As a result, well head Reynolds and Weber numbers cannot have an important influence on performance. The ratios of hole diameter to collector dimensions may or may not be important, but this cannot be determined in the tests we have done using only a single bottom-mounted collector. For this collector then, the important independent dimensionless variables are the hole Froude number and the phase ratio. Table 2 shows the results of the observed leakage tests for different hole Froude numbers and phase ratios. If each of these independent variables are large enough, no leakage will occur through the holes in the sides of the collector.

Table 2

Hole Froude Number (F_h)	Phase Ratio (R)	Remarks
1.14	0.137	No leakage
2.14	0.062	No leakage
2.51	0.036	No leakage
0.50	0.342	No leakage
0.28	0.193	Small leakage
0.50	0.102	Moderate leakage
0.36	0.058	Severe leakage
0.27	0.022	Severe leakage

8. The Gas Separating Collector

The results of the tests of oil collection performance for open bottom collectors shows that for a given Froude number, performance is degraded as the phase ratio is decreased. The reasons for this have been described previously. The separating collector, described here and shown in Fig. 6 was designed to reduce these effects. Control of the separation is achieved by means of the valve on the gas riser. As this valve is closed the interface between the bubble flow zone and the mist flow zone in the inner cone is lowered. If this interface is sufficiently low, essentially no liquid will travel through the gas riser. Furthermore, as the interface is made lower and lower, some of the gas tends to escape from inside the inner cone into the outer cone. It is this escaping gas which provides the gas lift in the liquid riser and drives the liquid collection process.

A limited number of experiments on this separating collector were carried out. The same riser that was used for the open bottom collector tests was used for the liquid riser. Its valve was in the full open condition which was the condition for the highest liquid collection rates in all of the tests with the open bottom collectors. A pipe with an inside diameter of 3/4" was used for the gas riser and this pipe itself extending through the height of the test tank provided enough resistance to prevent liquid from flowing through the gas riser. Nearly all of the gas came through the gas riser and a small amount escaped into the outer cone.

The initial tests of the separating collector reported here were done to determine its feasibility. We did not vary the resistance in the gas riser to optimize conditions for each gas flow rate. The test conditions and results are shown in Table 3. Even though we took no special steps to optimize the resistance in the gas riser, the total collected liquid flow rate was greater for every test with the separating collector than for any of the tests with a single cone collector. Although the collected liquid flow rate diminished with increasing gas flow rate, it always remained greater than for cases with a single collector. The most important result is the fact that the fraction of escaping oil that is collected does not diminish as the gas flow rate is increased. The detrimental effect of decreasing phase ratio for the single cone collectors is eliminated in the separating collector. All of the tests with the separating collector had nearly the same Froude number. The fraction of escaping oil collected is comparable to that for a single cone collector operating at the same Froude number, but with a favorable phase ratio. The separating collector eliminates the necessity of a favorable phase ratio.

9. Concluding Discussion

Subsea collection of the oil from the blowout of an offshore well is feasible. Collecting a high percentage of the blown out oil requires adequately large Froude numbers and phase ratios. The general relationship between the fraction of the blowout oil collected and the Froude number and the phase ratio are shown in Fig. 10.

Achieving a high Froude number requires a high liquid flow rate and a small distance between the well head and the bottom of the collector. To achieve a specific Froude number, the closer the collector is to the well head, the smaller can be the collected liquid flow rate. Generally speaking, the collection of large liquid flow rates requires a large diameter riser with a relatively small total lift above the sea surface. Inasmuch as the Froude number scaling involves the collected liquid flow rate divided by the 5/2's power of the collector height, the required liquid flow rate for a specific Froude number is very highly dependent on the height of the collector and as a result the total system size and cost can be minimized by minimization of this height.

With a single cone open bottom collector, when the amount of gas going through the system is large, the collected liquid flow rate must generally be extremely large if a high collection efficiency is to be achieved. For typical blowout conditions this would result in the need for an extremely large diameter riser or a group of smaller risers in parallel. However, this detrimental effect of high gas flow rate can be eliminated by the use of a separating collector of the type described in this report for which most of the gas is separated from the remainder of the flow in the collector and this gas comes to the surface through a separate riser from the one which carries liquid.

APPENDIX A

Raw Data for Oil Collection by the Single Cone Open Bottom Collectors

Each row of data contains seven numbers which are:

Collector number
Height of collector above nozzle (model wellhead) in inches
Nozzle inside diameter in inches
Airflow rate in SCFM
Blowout oil flow rate in GPM
Collected oil flow rate in GPM
Total collected liquid (oil + water) flow rate in GPM

1	7.0	0.364	2.4	0.50	0.40	18.2
1	7.0	0.364	2.4	1.0	0.77	15.6
1	7.0	0.364	2.4	1.5	1.11	15.7
1	7.0	0.364	2.3	2.0	1.6	16.4
1	7.0	0.364	2.4	0.5	0.25	8.8
1	7.0	0.364	2.4	1.0	0.64	8.3
1	7.0	0.364	2.4	1.5	0.80	8.4
1	7.0	0.364	2.3	2.0	1.15	9.1
1	7.0	0.364	2.3	2.5	1.4	9.3
1	7.0	0.364	2.4	1.0	0.36	4.1
1	7.0	0.364	2.4	1.5	0.44	4.0
1	7.0	0.364	2.3	2.0	0.69	4.1
1	7.0	0.364	2.3	2.5	0.92	4.3
1	7.0	0.364	4.8	0.5	0.37	15.9
1	7.0	0.364	4.8	1.0	0.74	16.6
1	7.0	0.364	4.7	1.5	0.97	17.6
1	7.0	0.364	4.7	2.0	1.43	19.7
1	7.0	0.364	4.8	0.5	0.19	8.3
1	7.0	0.364	4.8	1.0	0.44	9.2
1	7.0	0.364	4.7	1.5	0.87	9.6
1	7.0	0.364	4.7	2.0	1.08	9.0
1	7.0	0.364	4.6	2.5	1.07	9.0
1	7.0	0.364	4.8	0.5	0.17	4.3
1	7.0	0.364	4.8	1.0	0.32	4.8
1	7.0	0.364	4.7	1.5	0.58	4.8
1	7.0	0.364	4.7	2.0	0.65	4.6
1	7.0	0.364	4.6	2.5	0.71	4.3
1	7.0	0.364	7.0	0.5	0.24	16.7
1	7.0	0.364	6.9	1.0	0.58	19.0
1	7.0	0.364	6.8	1.5	0.87	18.5
1	7.0	0.364	6.7	2.0	1.11	16.7
1	7.0	0.364	6.5	2.5	1.20	16.6
1	7.0	0.364	7.0	0.5	0.18	8.4
1	7.0	0.364	6.9	1.0	0.29	8.5
1	7.0	0.364	6.8	1.5	0.41	8.5
1	7.0	0.364	6.7	2.0	0.66	8.9
1	7.0	0.364	6.5	2.5	0.85	9.3
1	7.0	0.364	7.0	0.5	0.12	3.9
1	7.0	0.364	6.9	1.0	0.20	4.0
1	7.0	0.364	6.8	1.5	0.17	3.6
1	7.0	0.364	6.7	2.0	0.23	3.8
1	7.0	0.364	6.5	2.5	0.30	4.2
1	7.0	0.364	9.9	0.5	0.22	17.8
1	7.0	0.364	9.7	1.0	0.46	18.1
1	7.0	0.364	9.4	1.5	0.69	16.2
1	7.0	0.364	9.1	2.0	0.93	16.8
1	7.0	0.364	8.8	2.5	1.30	17.4
1	7.0	0.364	9.9	0.5	0.11	8.7
1	7.0	0.364	9.7	1.0	0.22	9.1
1	7.0	0.364	9.4	1.5	0.43	9.1
1	7.0	0.364	9.1	2.0	0.58	9.0
1	7.0	0.364	8.8	2.5	0.68	8.9
1	7.0	0.364	9.9	0.5	0.04	2.9
1	7.0	0.364	9.7	1.0	0.08	3.4
1	7.0	0.364	9.4	1.5	0.17	3.3

1	7.0	0.364	9.1	2.0	0.25	3.3
1	7.0	0.364	14.7	0.5	0.19	14.9
1	7.0	0.364	14.3	1.0	0.43	16.1
1	7.0	0.364	13.8	1.5	0.58	15.7
1	7.0	0.364	12.8	2.5	1.10	16.6
1	7.0	0.364	14.7	0.5	0.10	8.3
1	7.0	0.364	14.3	1.0	0.20	8.6
1	7.0	0.364	13.8	1.5	0.37	9.0
1	7.0	0.364	13.3	2.0	0.48	8.9
1	7.0	0.364	12.8	2.5	0.69	9.0
1	7.0	0.364	13.8	1.5	0.53	5.9
1	7.0	0.364	13.3	2.0	0.74	6.5
1	7.0	0.364	12.8	2.5	0.81	6.4
1	7.0	0.364	14.7	0.5	0.13	4.2
1	7.0	0.364	13.8	1.5	0.47	5.1
1	7.0	0.364	13.3	2.0	0.55	4.9
1	7.0	0.364	12.8	2.5	0.67	4.7
1	7.0	0.364	19.2	0.5	0.21	13.9
1	7.0	0.364	18.4	1.0	0.40	14.7
1	7.0	0.364	17.6	1.5	0.61	14.6
1	7.0	0.364	16.8	2.0	0.77	14.0
1	7.0	0.364	16.0	2.5	1.07	14.4
1	7.0	0.364	19.2	0.5	0.19	6.3
1	7.0	0.364	18.4	1.0	0.44	8.1
1	7.0	0.364	17.6	1.5	0.75	8.4
1	7.0	0.364	16.8	2.0	1.02	9.2
1	7.0	0.364	16.0	2.5	1.20	9.9
1	7.0	0.364	19.2	0.5	0.14	4.5
1	7.0	0.364	18.4	1.0	0.31	5.0
1	7.0	0.364	17.6	1.5	0.46	4.9
1	7.0	0.364	16.8	2.0	0.56	4.9
1	7.0	0.364	16.0	2.5	0.66	5.0
1	7.0	0.622	2.4	1.0	0.71	15.33
1	7.0	0.622	2.4	1.5	1.09	16.57
1	7.0	0.622	2.4	2.0	1.36	16.56
1	7.0	0.622	2.4	2.5	1.85	16.64
1	7.0	0.622	2.4	0.5	0.32	10.12
1	7.0	0.622	2.4	1.0	0.67	9.2
1	7.0	0.622	2.4	1.5	0.87	9.3
1	7.0	0.622	2.4	2.0	1.64	10.9
1	7.0	0.622	2.4	2.5	1.96	10.1
1	7.0	0.622	2.4	0.5	0.21	5.1
1	7.0	0.622	2.4	1.0	0.38	4.9
1	7.0	0.622	2.4	1.5	0.82	5.2
1	7.0	0.622	2.4	2.0	0.83	4.9
1	7.0	0.622	2.4	2.5	1.09	5.2
1	7.0	0.824	2.4	1.0	0.49	15.84
1	7.0	0.824	2.4	1.5	0.75	14.7
1	7.0	0.824	2.4	2.0	1.06	15.60
1	7.0	0.824	2.4	2.5	1.26	15.40
1	7.0	0.824	2.4	1.0	0.24	8.89
1	7.0	0.824	2.4	1.5	0.59	9.43
1	7.0	0.824	2.4	2.0	0.98	10.18
1	7.0	0.824	2.4	2.5	1.284	10.00
1	7.0	0.824	2.4	1.0	0.20	5.60

1	7.0	0.824	2.4	1.5	0.42	5.60
1	7.0	0.824	2.4	2.0	0.75	5.7
1	7.0	0.824	2.4	2.5	1.16	5.8
1	12.0	0.364	2.4	0.5	0.317	13.94
1	12.0	0.364	2.4	1.5	0.801	12.70
1	12.0	0.364	2.3	2.0	1.06	13.56
1	12.0	0.364	2.3	2.5	1.11	13.79
1	12.0	0.364	2.4	0.5	0.193	7.96
1	12.0	0.364	2.4	1.0	0.404	8.17
1	12.0	0.364	2.4	1.5	0.621	8.30
1	12.0	0.364	2.3	2.0	0.729	8.30
1	12.0	0.364	2.3	2.5	0.848	9.74
1	12.0	0.364	2.4	0.5	0.294	5.43
1	12.0	0.364	2.4	1.0	0.433	5.67
1	12.0	0.364	2.4	1.5	0.487	5.60
1	12.0	0.364	2.3	2.0	0.488	5.73
1	12.0	0.364	2.3	2.5	0.691	6.03
1	21.0	0.364	2.4	1.0	0.19	13.4
1	21.0	0.364	2.4	1.5	0.25	11.1
1	21.0	0.364	2.3	2.0	0.33	11.3
1	21.0	0.364	2.3	2.5	0.42	12.75
1	21.0	0.364	2.4	0.5	0.10	10.97
1	21.0	0.364	2.4	1.0	0.15	10.01
1	21.0	0.364	2.4	1.5	0.24	9.82
1	21.0	0.364	2.3	2.0	0.28	9.24
1	21.0	0.364	2.3	2.5	0.34	8.80
1	21.0	0.364	2.4	0.5	0.064	8.37
1	21.0	0.364	2.4	1.0	0.124	7.94
1	21.0	0.364	2.4	1.5	0.175	8.29
1	21.0	0.364	2.3	2.0	0.218	8.14
1	21.0	0.364	2.3	2.5	0.38	9.19
1	7.0	0.622	10.0	1.0	0.57	16.1
1	7.0	0.622	10.0	1.5	0.86	17.7
1	7.0	0.622	10.0	2.0	1.07	16.3
1	7.0	0.622	10.0	2.5	1.24	15.5
1	7.0	0.622	10.0	0.5	0.14	9.7
1	7.0	0.622	10.0	1.0	0.21	8.7
1	7.0	0.622	10.0	1.5	0.61	9.9
1	7.0	0.622	10.0	2.0	0.81	9.6
1	7.0	0.622	10.0	2.5	0.91	9.3
1	7.0	0.622	10.0	1.0	0.26	4.4
1	7.0	0.622	10.0	1.5	0.21	3.7
1	7.0	0.622	10.0	2.0	0.33	4.3
1	7.0	0.622	10.0	2.5	0.45	4.1
1	7.0	0.824	10.3	1.0	0.11	16.6
1	7.0	0.824	10.1	2.0	0.65	15.5
1	7.0	0.824	10.0	2.5	1.10	15.8
1	7.0	0.824	10.3	1.0	0.19	9.7
1	7.0	0.824	10.2	1.5	0.31	9.1
1	7.0	0.824	10.1	2.0	0.51	8.6
1	7.0	0.824	10.0	2.5	0.86	9.6
1	7.0	0.824	10.3	1.0	0.07	4.82
1	7.0	0.824	10.2	1.5	0.25	4.90
1	7.0	0.824	10.1	2.0	0.38	5.22
1	7.0	0.824	10.2	1.5	0.615	15.8

1	12.0	0.364	9.9	0.5	0.137	16.0
1	12.0	0.364	9.7	1.0	0.266	14.4
1	12.0	0.364	9.4	1.5	0.379	15.4
1	12.0	0.364	9.1	2.0	0.498	16.06
1	12.0	0.364	8.8	2.5	0.634	17.4
1	12.0	0.364	9.9	0.5	0.123	9.6
1	12.0	0.364	9.7	1.0	0.178	8.5
1	12.0	0.364	9.4	1.5	0.226	8.71
1	12.0	0.364	9.1	2.0	0.310	9.12
1	12.0	0.364	8.8	2.5	0.384	8.27
1	12.0	0.364	9.9	0.5	0.071	3.80
1	12.0	0.364	9.7	1.0	0.069	3.63
1	12.0	0.364	9.1	2.0	0.141	4.23
1	12.0	0.364	8.8	2.5	0.429	5.23
1	21.0	0.364	9.9	0.5	0.042	13.07
1	21.0	0.364	9.7	1.0	0.097	14.86
1	21.0	0.364	9.4	1.5	0.166	14.83
1	21.0	0.364	9.1	2.0	0.22	15.27
1	21.0	0.364	8.8	2.5	0.28	16.76
1	21.0	0.364	9.9	0.5	0.046	7.69
1	21.0	0.364	9.7	1.0	0.064	8.61
1	21.0	0.364	9.4	1.5	0.136	10.38
1	21.0	0.364	9.1	2.0	0.139	9.46
1	21.0	0.364	8.8	2.5	0.148	8.45
1	21.0	0.364	9.9	0.5	0.026	5.92
1	21.0	0.364	9.7	1.0	0.053	5.94
1	21.0	0.364	9.4	1.5	0.059	4.68
1	21.0	0.364	9.1	2.0	0.102	5.55
1	21.0	0.364	8.8	2.5	0.101	4.65
1	7.0	0.622	20.0	0.5	0.11	12.56
1	7.0	0.622	20.0	1.0	0.22	15.33
1	7.0	0.622	20.0	1.5	0.37	15.23
1	7.0	0.622	20.0	2.0	0.60	15.4
1	7.0	0.622	20.0	2.5	0.65	14.15
1	7.0	0.622	20.0	0.5	0.08	7.73
1	7.0	0.622	20.0	1.0	0.14	7.90
1	7.0	0.622	20.0	1.5	0.23	8.01
1	7.0	0.622	20.0	2.0	0.29	7.15
1	7.0	0.622	20.0	2.5	0.40	8.00
1	7.0	0.622	20.0	0.5	0.03	3.40
1	7.0	0.622	20.0	1.0	0.05	3.19
1	7.0	0.622	20.0	1.5	0.09	3.28
1	7.0	0.622	20.0	2.0	0.16	2.93
1	7.0	0.824	20.7	1.0	0.194	13.84
1	7.0	0.824	19.8	1.5	0.33	12.66
1	7.0	0.824	19.8	2.0	0.52	14.60
1	7.0	0.824	19.7	2.5	0.75	14.83
1	7.0	0.824	20.7	1.0	0.12	7.2
1	7.0	0.824	19.8	1.5	0.22	7.4
1	7.0	0.824	19.8	2.0	0.30	7.6
1	7.0	0.824	19.7	2.5	0.46	9.1
1	7.0	0.824	20.7	1.0	0.06	3.6
1	7.0	0.824	19.8	1.5	0.18	5.24
1	7.0	0.824	19.8	2.0	0.22	4.7
1	7.0	0.824	19.7	2.5	0.34	5.0

1	7.0	0.824	20.7	1.0	0.08	3.3
1	12.0	0.364	19.2	0.5	0.12	10.24
1	12.0	0.364	18.4	1.0	0.28	16.13
1	12.0	0.364	17.6	1.5	0.40	13.9
1	12.0	0.364	16.8	2.0	0.56	15.9
1	12.0	0.364	16.0	2.5	0.76	17.74
1	12.0	0.364	19.2	0.5	0.09	8.79
1	12.0	0.363	18.4	1.0	0.19	7.03
1	12.0	0.364	17.6	1.5	0.29	7.40
1	12.0	0.364	16.8	2.0	0.72	10.4
1	12.0	0.364	16.0	2.5	1.0	7.87
1	12.0	0.364	18.4	1.0	0.22	5.41
1	12.0	0.364	17.6	1.5	0.40	6.47
1	12.0	0.364	16.8	2.0	0.50	6.12
1	12.0	0.364	16.0	2.5	0.50	6.15
1	21.0	0.364	19.2	0.5	0.02	14.3
1	21.0	0.364	18.4	1.0	0.05	14.5
1	21.0	0.364	17.6	1.5	0.11	14.6
1	21.0	0.364	16.8	2.0	0.15	13.3
1	21.0	0.364	16.0	2.5	0.29	15.1
1	21.0	0.364	19.2	0.5	0.03	7.3
1	21.0	0.364	18.4	1.0	0.06	6.8
1	21.0	0.364	17.6	1.5	0.09	6.9
1	21.0	0.364	16.8	2.0	0.14	8.5
1	21.0	0.364	16.0	2.5	0.17	7.94
1	21.0	0.364	19.2	0.5	0.01	2.16
1	21.0	0.364	18.4	1.0	0.02	2.40
1	21.0	0.364	17.6	1.5	0.03	2.72
1	21.0	0.364	16.8	2.0	0.03	2.79
1	21.0	0.364	16.0	2.5	0.05	3.06
2	7.0	0.364	2.4	0.50	0.48	14.5
2	7.0	0.364	2.4	1.5	1.20	16.1
2	7.0	0.364	2.3	2.0	1.5	15.4
2	7.0	0.364	2.4	0.5	0.23	8.4
2	7.0	0.364	2.4	1.0	0.51	8.4
2	7.0	0.364	2.4	1.5	0.80	8.4
2	7.0	0.364	2.3	2.0	1.13	8.3
2	7.0	0.364	2.4	0.5	0.18	3.8
2	7.0	0.364	2.4	1.0	0.48	4.0
2	7.0	0.364	2.4	1.5	0.29	3.8
2	7.0	0.364	2.3	2.0	0.52	3.7
2	7.0	0.364	2.3	2.5	0.56	3.6
2	7.0	0.364	9.9	0.5	0.23	14.9
2	7.0	0.364	9.7	1.0	0.47	16.4
2	7.0	0.364	9.4	1.5	0.69	16.1
2	7.0	0.364	8.8	2.5	1.0	15.7
2	7.0	0.364	9.9	0.5	0.12	8.0
2	7.0	0.364	9.7	1.0	0.20	7.6
2	7.0	0.364	9.4	1.5	0.31	7.7
2	7.0	0.364	9.1	2.0	0.44	8.2
2	7.0	0.364	8.8	2.5	0.58	8.5
2	7.0	0.364	9.9	0.5	0.07	3.1
2	7.0	0.364	9.7	1.0	0.12	3.2
2	7.0	0.364	9.4	1.5	0.18	3.2
2	7.0	0.364	9.1	2.0	0.25	3.0

2	7.0	0.364	8.8	2.5	0.24	3.3
2	7.0	0.364	19.2	0.5	0.15	12.5
2	7.0	0.364	18.4	1.0	0.26	9.8
2	7.0	0.364	17.6	1.5	0.53	14.0
2	7.0	0.364	16.8	2.0	0.64	13.7
2	7.0	0.364	16.0	2.5	0.93	14.9
2	7.0	0.364	19.2	0.5	0.099	7.03
2	7.0	0.364	18.4	1.0	0.161	6.59
2	7.0	0.364	17.6	1.5	0.247	6.85
2	7.0	0.364	16.8	2.0	0.412	6.84
2	7.0	0.364	16.0	2.5	0.643	7.80
2	7.0	0.364	19.2	0.5	0.037	1.49
2	7.0	0.364	18.4	1.0	0.058	1.57
2	7.0	0.364	17.6	1.5	0.094	1.91
2	7.0	0.364	16.8	2.0	0.136	2.10
2	7.0	0.364	16.0	2.5	0.153	1.76
3	7.0	0.364	2.4	1.0	0.803	15.57
3	7.0	0.364	2.4	1.5	1.23	16.43
3	7.0	0.364	2.3	2.0	1.768	16.7
3	7.0	0.364	2.3	2.5	2.15	18.8
3	7.0	0.364	2.2	3.0	2.27	17.89
3	7.0	0.364	2.4	0.5	0.27	9.51
3	7.0	0.364	2.4	1.0	0.81	10.15
3	7.0	0.364	2.4	1.5	1.26	9.67
3	7.0	0.364	2.3	2.0	1.53	9.97
3	7.0	0.364	2.3	2.5	1.65	9.89
3	7.0	0.364	2.2	3.0	1.49	10.3
3	7.0	0.364	2.4	0.5	0.30	5.1
3	7.0	0.364	2.4	1.0	0.49	5.6
3	7.0	0.364	2.4	1.5	0.625	5.6
3	7.0	0.364	2.3	2.0	0.97	5.5
3	7.0	0.364	2.3	2.5	0.98	5.5
3	7.0	0.364	4.8	0.5	0.37	17.2
3	7.0	0.364	4.8	1.0	0.78	16.2
3	7.0	0.364	4.7	1.5	1.14	18.2
3	7.0	0.364	4.7	2.0	1.49	18.16
3	7.0	0.364	4.6	2.5	1.74	18.30
3	7.0	0.364	4.8	0.5	0.22	10.14
3	7.0	0.364	4.8	1.0	0.55	10.24
3	7.0	0.364	4.7	1.5	0.78	10.5
3	7.0	0.364	4.7	2.0	0.89	10.4
3	7.0	0.364	4.6	2.5	1.05	10.37
3	7.0	0.364	4.5	3.0	1.17	10.24
3	7.0	0.364	4.8	0.5	0.16	6.23
3	7.0	0.364	4.8	1.0	0.31	5.97
3	7.0	0.364	4.7	1.5	0.49	5.85
3	7.0	0.364	4.7	2.0	0.60	6.14
3	7.0	0.364	4.6	2.5	0.70	6.6
3	7.0	0.364	4.5	3.0	0.91	6.6
3	7.0	0.364	7.0	0.5	0.19	17.3
3	7.0	0.364	6.9	1.0	0.37	16.9
3	7.0	0.364	6.8	1.5	0.655	18.2
3	7.0	0.364	6.7	2.0	1.06	20.2
3	7.0	0.364	6.5	2.5	1.055	17.35
3	7.0	0.364	6.2	3.0	1.51	19.1

3	7.0	0.364	7.0	0.5	0.12	9.0
3	7.0	0.364	6.9	1.0	0.22	8.9
3	7.0	0.364	6.8	1.5	0.32	8.6
3	7.0	0.364	6.7	2.0	0.48	10.2
3	7.0	0.364	6.5	2.5	0.64	9.9
3	7.0	0.364	6.2	3.0	0.84	10.1
3	7.0	0.364	7.0	0.5	0.05	3.5
3	7.0	0.364	6.9	1.0	0.08	3.4
3	7.0	0.364	6.8	1.5	0.14	3.4
3	7.0	0.364	6.7	2.0	0.19	3.6
3	7.0	0.364	6.5	2.5	0.24	3.3
3	7.0	0.364	6.2	3.0	0.46	3.75
3	7.0	0.364	9.9	0.5	0.18	16.2
3	7.0	0.364	9.7	1.0	0.37	17.8
3	7.0	0.364	9.4	1.5	0.71	16.8
3	7.0	0.364	9.1	2.0	0.94	18.0
3	7.0	0.364	8.8	2.5	1.19	17.8
3	7.0	0.364	8.4	3.0	1.32	16.9
3	7.0	0.364	9.9	0.5	0.12	9.3
3	7.0	0.364	9.7	1.0	0.26	9.7
3	7.0	0.364	9.4	1.5	0.40	9.7
3	7.0	0.364	9.1	2.0	0.56	10.2
3	7.0	0.364	8.8	2.5	0.71	9.3
3	7.0	0.364	8.4	3.0	0.81	9.55
3	7.0	0.364	9.9	0.5	0.09	6.35
3	7.0	0.364	9.7	1.0	0.17	5.7
3	7.0	0.364	9.4	1.5	0.26	6.0
3	7.0	0.364	9.1	2.0	0.38	6.1
3	7.0	0.364	8.8	2.5	0.54	5.7
3	7.0	0.364	8.4	3.0	0.66	6.3
3	7.0	0.364	14.7	0.5	0.18	14.6
3	7.0	0.364	14.3	1.0	0.42	16.0
3	7.0	0.364	13.8	1.5	0.67	16.0
3	7.0	0.364	13.3	2.0	0.9	15.95
3	7.0	0.364	12.8	2.5	1.05	15.2
3	7.0	0.364	14.7	0.5	0.16	8.1
3	7.0	0.364	14.3	1.0	0.29	8.2
3	7.0	0.364	13.8	1.5	0.5	7.9
3	7.0	0.364	13.3	2.0	0.67	8.8
3	7.0	0.364	12.8	2.5	0.89	8.7
3	7.0	0.364	14.7	0.5	0.16	4.0
3	7.0	0.364	14.3	1.0	0.31	4.3
3	7.0	0.364	13.8	1.5	0.5	4.6
3	7.0	0.364	13.3	2.0	0.68	5.0
3	7.0	0.364	12.8	2.5	0.71	4.6
3	7.0	0.364	19.2	0.5	0.19	13.4
3	7.0	0.364	18.4	1.0	0.43	15.4
3	7.0	0.364	17.6	1.5	0.68	15.8
3	7.0	0.364	16.8	2.0	0.91	16.3
3	7.0	0.364	16.0	2.5	1.09	17.6
3	7.0	0.364	19.2	0.5	0.17	6.33
3	7.0	0.364	18.4	1.0	0.34	6.7
3	7.0	0.364	16.8	2.0	0.64	7.0
3	7.0	0.364	16.0	2.5	0.91	7.5
3	7.0	0.364	19.2	0.5	0.14	3.8

3	7.0	0.364	18.4	1.0	0.30	4.1
3	7.0	0.364	17.6	1.5	0.46	4.0
3	7.0	0.364	16.8	2.0	0.60	4.2
3	7.0	0.364	16.0	2.5	0.70	4.6
4	7.0	0.364	2.4	1.0	0.89	16.8
4	7.0	0.364	2.3	2.0	1.63	16.2
4	7.0	0.364	2.3	2.5	1.95	15.4
4	7.0	0.364	2.4	1.0	0.62	8.7
4	7.0	0.364	2.4	1.5	0.91	9.4
4	7.0	0.364	2.3	2.0	1.28	9.8
4	7.0	0.364	2.3	2.5	1.3	9.2
4	7.0	0.364	2.4	0.5	0.27	4.6
4	7.0	0.364	2.4	1.0	0.46	4.55
4	7.0	0.364	2.4	1.5	0.62	4.3
4	7.0	0.364	2.3	2.0	0.73	4.8
4	7.0	0.364	9.9	0.5	0.5	16.07
4	7.0	0.364	9.7	1.0	0.72	16.57
4	7.0	0.364	9.4	1.5	1.05	15.91
4	7.0	0.364	9.1	2.0	1.54	17.64
4	7.0	0.364	8.8	2.5	1.72	16.09
4	7.0	0.364	9.9	0.5	0.22	8.25
4	7.0	0.364	9.7	1.0	0.47	7.94
4	7.0	0.364	9.4	1.5	0.71	8.11
4	7.0	0.364	8.8	2.5	1.4	8.6
4	7.0	0.364	9.7	1.0	0.38	4.11
4	7.0	0.364	9.4	1.5	0.63	4.6
4	7.0	0.364	9.1	2.0	0.85	4.6
4	7.0	0.364	8.8	2.5	0.94	4.7
4	7.0	0.364	19.2	0.5	0.35	16.5
4	7.0	0.364	18.4	1.0	0.67	15.6
4	7.0	0.364	17.6	1.5	1.09	15.7
4	7.0	0.364	16.8	2.0	1.40	16.2
4	7.0	0.364	16.0	2.5	1.92	17.3
4	7.0	0.364	19.2	0.5	0.31	8.10
4	7.0	0.364	18.4	1.0	0.65	7.6
4	7.0	0.364	17.6	1.5	1.00	8.14
4	7.0	0.364	16.8	2.0	1.39	9.3
4	7.0	0.364	16.0	2.5	1.75	9.7
4	7.0	0.364	19.2	0.5	0.23	4.74
4	7.0	0.364	18.4	1.0	0.49	4.79
4	7.0	0.364	17.6	1.5	0.72	4.8
4	7.0	0.364	16.0	2.5	1.04	4.8
4	3.0	0.364	9.9	0.5	0.5	17.0
4	3.0	0.364	9.4	1.5	1.45	17.3
4	3.0	0.364	8.8	2.5	2.46	19.4
4	3.0	0.364	9.9	0.5	0.39	11.7
4	3.0	0.364	9.4	1.5	1.32	12.0
4	3.0	0.364	8.8	2.50	2.31	11.8
4	3.0	0.364	9.4	1.5	1.09	4.08
4	3.0	0.364	8.8	2.5	1.81	4.90
4	12.0	0.364	9.9	0.5	0.15	19.2
4	12.0	0.364	9.4	1.5	0.55	18.1
4	12.0	0.364	8.8	2.5	0.84	17.3
4	12.0	0.364	9.9	0.5	0.07	9.2
4	12.0	0.364	9.4	1.5	0.31	9.3

APPENDIX B

Averaged Data for Oil Collection by Single Cone Open Bottom Collectors

Each row of data is generated by averaging the 3,4,5 or 6 rows of data in Appendix A where only the nominal oil flow rate was varied. Since the oil flow affected nozzle resistance, changing the oil flow made small changes in the actual air flow as shown in Appendix A. This small variation is accounted for in the averaging process.

Each row of data contains eight numbers which are:

Collector number

Height of collector above nozzle (model wellhead) in inches

Nozzle inside diameter in inches

Airflow rate in SCFM

Averaged oil flow rate in GPM

Averaged collected oil flow rate in GPM

Averaged total liquid flow rate in GPM

Averaged fraction of blowout oil that is collected.

1	7.000	0.364	2.375	1.250	0.970	16.475	0.777
1	7.000	0.364	2.350	1.750	0.997	8.775	0.577
1	7.000	0.364	2.333	2.000	0.683	4.133	0.335
1	7.000	0.364	4.733	1.500	1.047	17.967	0.701
1	7.000	0.364	4.700	1.750	0.865	9.200	0.497
1	7.000	0.364	4.700	1.750	0.565	4.625	0.329
1	7.000	0.364	6.725	1.750	0.940	17.700	0.549
1	7.000	0.364	6.725	1.750	0.552	8.800	0.308
1	7.000	0.364	6.725	1.750	0.225	3.900	0.137
1	7.000	0.364	9.250	1.750	0.845	17.125	0.476
1	7.000	0.364	9.250	1.750	0.477	9.025	0.267
1	7.000	0.364	9.400	1.500	0.167	3.333	0.106
1	7.000	0.364	13.633	1.667	0.703	16.133	0.419
1	7.000	0.364	13.550	1.750	0.435	8.875	0.241
1	7.000	0.364	13.050	2.250	0.775	6.450	0.347
1	7.000	0.364	13.300	2.000	0.563	4.900	0.285
1	7.000	0.364	17.200	1.750	0.712	14.425	0.405
1	7.000	0.364	17.200	1.750	0.852	8.900	0.482
1	7.000	0.364	17.200	1.750	0.497	4.950	0.290
1	7.000	0.622	2.400	2.000	1.433	16.590	0.716
1	7.000	0.622	2.400	1.750	1.285	9.875	0.713
1	7.000	0.622	2.400	1.750	0.780	5.050	0.444
1	7.000	0.824	2.400	2.000	1.023	15.233	0.511
1	7.000	0.824	2.400	2.000	0.951	9.870	0.466
1	7.000	0.824	2.400	2.000	0.777	5.700	0.373
1	12.000	0.364	2.333	2.000	0.990	13.350	0.503
1	12.000	0.364	2.350	1.750	0.650	8.627	0.380
1	12.000	0.364	2.350	1.750	0.525	5.757	0.320
1	21.000	0.364	2.333	2.000	0.333	11.717	0.167
1	21.000	0.364	2.350	1.750	0.252	9.467	0.146
1	21.000	0.364	2.350	1.750	0.224	8.390	0.125
1	7.000	0.622	10.000	2.000	1.057	16.500	0.535
1	7.000	0.622	10.000	1.750	0.635	9.375	0.346
1	7.000	0.622	10.000	2.000	0.330	4.033	0.162
1	7.000	0.824	10.100	2.000	0.788	15.700	0.392
1	7.000	0.824	10.100	2.000	0.560	9.100	0.269
1	7.000	0.824	10.150	1.750	0.315	5.060	0.178
1	12.000	0.364	9.250	1.750	0.444	15.815	0.255
1	12.000	0.364	9.250	1.750	0.274	8.650	0.159
1	12.000	0.364	9.200	1.833	0.213	4.363	0.104
1	21.000	0.364	9.250	1.750	0.191	15.430	0.107
1	21.000	0.364	9.250	1.750	0.122	9.225	0.071
1	21.000	0.364	9.250	1.750	0.079	5.205	0.046
1	7.000	0.622	20.000	1.750	0.460	15.027	0.257
1	7.000	0.622	20.000	1.750	0.265	7.765	0.150
1	7.000	0.622	20.000	1.500	0.100	3.133	0.063
1	7.000	0.824	19.767	2.000	0.533	14.030	0.260
1	7.000	0.824	19.767	2.000	0.327	8.033	0.160
1	7.000	0.824	20.000	1.750	0.200	4.635	0.106
1	12.000	0.364	17.200	1.750	0.500	15.917	0.283
1	12.000	0.363	17.200	1.750	0.550	8.175	0.286
1	12.000	0.364	16.800	2.000	0.467	6.247	0.239
1	21.000	0.364	17.200	1.750	0.150	14.375	0.079
1	21.000	0.364	17.200	1.750	0.115	7.535	0.064
1	21.000	0.364	17.200	1.750	0.032	2.742	0.019

2	7.000	0.364	2.350	1.750	1.350	15.750	0.775
2	7.000	0.364	2.367	1.500	0.813	8.367	0.536
2	7.000	0.364	2.350	1.750	0.462	3.775	0.289
2	7.000	0.364	9.300	1.667	0.720	16.067	0.443
2	7.000	0.364	9.250	1.750	0.382	8.000	0.215
2	7.000	0.364	9.250	1.750	0.197	3.175	0.115
2	7.000	0.364	17.200	1.750	0.590	13.100	0.326
2	7.000	0.364	17.200	1.750	0.366	7.020	0.197
2	7.000	0.364	17.200	1.750	0.110	1.835	0.062
3	7.000	0.364	2.300	2.250	1.854	17.455	0.830
3	7.000	0.364	2.320	2.000	1.348	9.996	0.719
3	7.000	0.364	2.350	1.750	0.766	5.550	0.446
3	7.000	0.364	4.700	1.750	1.287	17.715	0.745
3	7.000	0.364	4.660	2.000	0.888	10.350	0.465
3	7.000	0.364	4.660	2.000	0.602	6.232	0.304
3	7.000	0.364	6.620	2.000	0.930	18.350	0.452
3	7.000	0.364	6.620	2.000	0.500	9.540	0.242
3	7.000	0.364	6.620	2.000	0.222	3.490	0.104
3	7.000	0.364	9.080	2.000	0.906	17.460	0.446
3	7.000	0.364	9.080	2.000	0.548	9.690	0.272
3	7.000	0.364	9.080	2.000	0.402	5.960	0.194
3	7.000	0.364	13.550	1.750	0.760	15.787	0.434
3	7.000	0.364	13.550	1.750	0.587	8.400	0.329
3	7.000	0.364	13.550	1.750	0.550	4.625	0.317
3	7.000	0.364	17.200	1.750	0.777	16.275	0.444
3	7.000	0.364	17.067	1.833	0.630	7.067	0.341
3	7.000	0.364	17.200	1.750	0.515	4.225	0.29[illegible]
4	7.000	0.364	2.300	2.250	1.790	15.800	0.797
4	7.000	0.364	2.333	2.000	1.163	9.467	0.589
4	7.000	0.364	2.367	1.500	0.603	4.550	0.413
4	7.000	0.364	9.250	1.750	1.257	16.552	0.719
4	7.000	0.364	9.300	1.667	0.860	8.217	0.501
4	7.000	0.364	9.100	2.000	0.807	4.633	0.407
4	7.000	0.364	17.200	1.750	1.270	16.200	0.716
4	7.000	0.364	17.200	1.750	1.197	8.685	0.678
4	7.000	0.364	17.333	1.667	0.750	4.797	0.462
4	3.000	0.364	9.100	2.000	1.955	18.350	0.975
4	3.000	0.364	9.100	2.000	1.815	11.900	0.902
4	3.000	0.364	8.800	2.500	1.810	4.900	0.724
4	12.000	0.364	9.100	2.000	0.695	17.700	0.351
4	12.000	0.364	9.100	2.000	0.405	9.100	0.203

APPENDIX C

Pressure Measurement Data for the Bottom Mounted Collector

This appendix presents the data from the pressure measurement tests with the bottom mounted collector. Pressure differences between inside the collector and outside were were measured at the three height locations shown in figure 5. The most important feature of the results is that for all tested conditions the average inside pressure is less than the average outside pressure. This condition of less pressure inside than outside is indicated by negative pressure differences (listed pressure difference = inside pressure - outside pressure). Thus, in use the pressure differences will drive the collector onto the sea bottom, rather than blow it off.

Each row of data represents one experimental condition. Each row contains six numbers which are:

Diameter of holes in collector sides (there were eight holes).
Airflow rate in standard cubic feet per second.
Collected water flow rate in cubic feet per second
Pressure difference at lowest measurement point.
Pressure difference at middle measurement point
Pressure difference at highest measurement point.

The units for the pressure differences between inside and outside are head in feet of water.

0.500	0.333	0.034	-0.354	-0.333	0.583
0.500	0.333	0.032	-0.458	-0.292	0.708
0.500	0.333	0.027	-0.500	-0.333	0.708
0.500	0.333	0.022	-0.542	-0.292	0.833
0.500	0.333	0.014	-0.625	-0.500	0.750
0.500	0.333	0.007	-0.292	0.208	0.833
0.500	0.167	0.045	-0.542	-0.458	0.125
0.500	0.167	0.036	-0.458	-0.375	0.292
0.500	0.167	0.031	-0.417	-0.333	0.333
0.500	0.167	0.027	-0.417	-0.333	0.396
0.500	0.167	0.019	-0.458	-0.375	0.458
0.500	0.167	0.010	-0.542	-0.375	0.500
0.500	0.080	0.042	-0.637	-0.721	-0.512
0.500	0.080	0.041	-0.525	-0.596	-0.342
0.500	0.080	0.036	-0.417	-0.467	-0.171
0.500	0.080	0.031	-0.292	-0.358	0.0
0.500	0.080	0.024	-0.200	-0.283	0.183
0.500	0.080	0.014	-0.229	-0.275	0.217
0.500	0.080	0.008	-0.313	-0.375	0.183
0.500	0.040	0.040	-0.542	-0.542	-0.458
0.500	0.040	0.038	-0.417	-0.417	-0.292
0.500	0.040	0.035	-0.333	-0.333	-0.167
0.500	0.040	0.030	-0.250	-0.250	-0.042
0.500	0.040	0.022	-0.125	-0.125	0.125
0.500	0.040	0.014	-0.125	-0.125	0.250
0.500	0.040	0.008	-0.125	-0.125	0.208
0.250	0.333	0.031	-1.833	-1.583	-0.583
0.250	0.333	0.027	-1.708	-1.417	-0.417
0.250	0.333	0.024	-1.583	-1.250	-0.167
0.250	0.333	0.019	-1.458	-1.083	0.0
0.250	0.333	0.015	-1.458	-0.875	0.333
0.250	0.333	0.012	-1.250	-0.500	0.792
0.250	0.167	0.038	-2.375	-2.250	-1.542
0.250	0.167	0.033	-2.042	-1.958	-1.167
0.250	0.167	0.033	-1.708	-1.667	-0.708
0.250	0.167	0.028	-1.417	-1.333	-0.500
0.250	0.167	0.018	-1.167	-1.042	-0.292
0.250	0.167	0.010	-1.208	-0.958	-0.250
0.250	0.167	0.005	-1.583	-1.583	-0.458

0.250	0.080	0.040	-2.375	-2.458	-2.125
0.250	0.080	0.038	-2.000	-2.083	-1.750
0.250	0.080	0.031	-1.625	-1.708	-1.292
0.250	0.080	0.030	-1.333	-1.417	-1.000
0.250	0.080	0.023	-0.958	-1.042	-0.542
0.250	0.080	0.014	-0.667	-0.750	-0.208
0.250	0.080	0.007	-0.625	-0.792	-0.125
0.250	0.040	0.038	-1.917	-1.875	-1.792
0.250	0.040	0.034	-1.667	-1.667	-1.542
0.250	0.040	0.030	-1.458	-1.417	-1.292
0.250	0.040	0.038	-1.333	-1.292	-1.083
0.250	0.040	0.022	-1.000	-0.917	-0.667
0.250	0.040	0.014	-0.604	-0.583	-0.333
0.250	0.040	0.010	-0.542	-0.500	-0.250
0.250	0.040	0.005	-0.417	-0.333	-0.083
0.125	0.333	0.027	-1.883	-1.717	-0.800
0.125	0.333	0.026	-2.258	-2.058	-1.100
0.125	0.333	0.024	-2.350	-2.150	-1.150
0.125	0.333	0.018	-2.375	-2.150	-1.208
0.125	0.333	0.014	-2.325	-2.050	-1.192
0.125	0.333	0.007	-2.183	-1.767	-1.133
0.125	0.167	0.033	-4.083	-4.083	-3.208
0.125	0.167	0.030	-3.521	-3.467	-2.604
0.125	0.167	0.028	-3.083	-3.063	-2.188
0.125	0.167	0.025	-2.583	-2.417	-1.625
0.125	0.167	0.018	-2.208	-2.104	-1.167
0.125	0.167	0.009	-2.975	-3.125	-2.042
0.125	0.080	0.045	-3.917	-3.633	-3.542
0.125	0.080	0.033	-3.500	-3.417	-3.125
0.125	0.080	0.030	-3.125	-3.000	-2.708
0.125	0.080	0.024	-2.708	-2.583	-2.250
0.125	0.080	0.021	-2.167	-2.083	-1.708
0.125	0.080	0.014	-1.500	-1.375	-0.917
0.125	0.080	0.010	-1.167	-1.083	-0.625
0.125	0.040	0.029	-2.583	-2.583	-2.375
0.125	0.040	0.028	-2.167	-2.183	-2.008
0.125	0.040	0.022	-1.858	-1.854	-1.667
0.125	0.040	0.018	-1.375	-1.375	-1.167
0.125	0.040	0.012	-0.958	-0.958	-0.708
0.125	0.040	0.007	-0.708	-0.708	-0.417

FIGURE 1. The Subsurface Cone Collector, Riser and Supporting Truss Used at the IXTOC Blowout in Campeche Bay

The collector with its open gas escape valve can be seen at the right. The risers with their individual valves can be seen going up the center of the truss. In use the end of the truss at the left of the photograph was attached to a fixed platform. The gas escape valve on the top of the collector was closed after the collector was above the wellhead and oil, gas and water travelled up the risers to a processing system on the platform as well as on a second platform connected to the first by a bridge. This second platform and the bridge can be seen in the backround of the photograph.

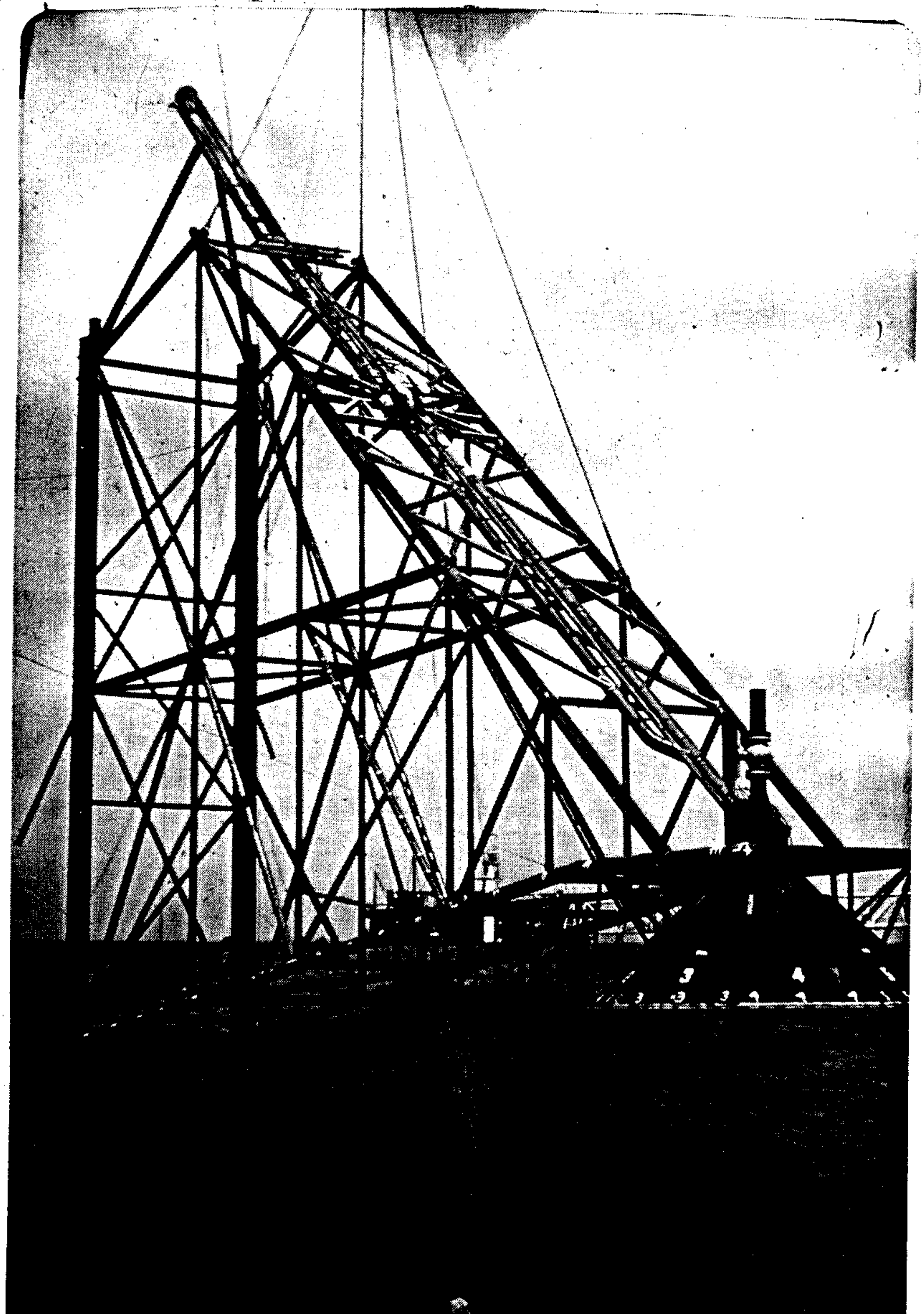


FIGURE 2. The Model Collectors That were Tested in the Experiments

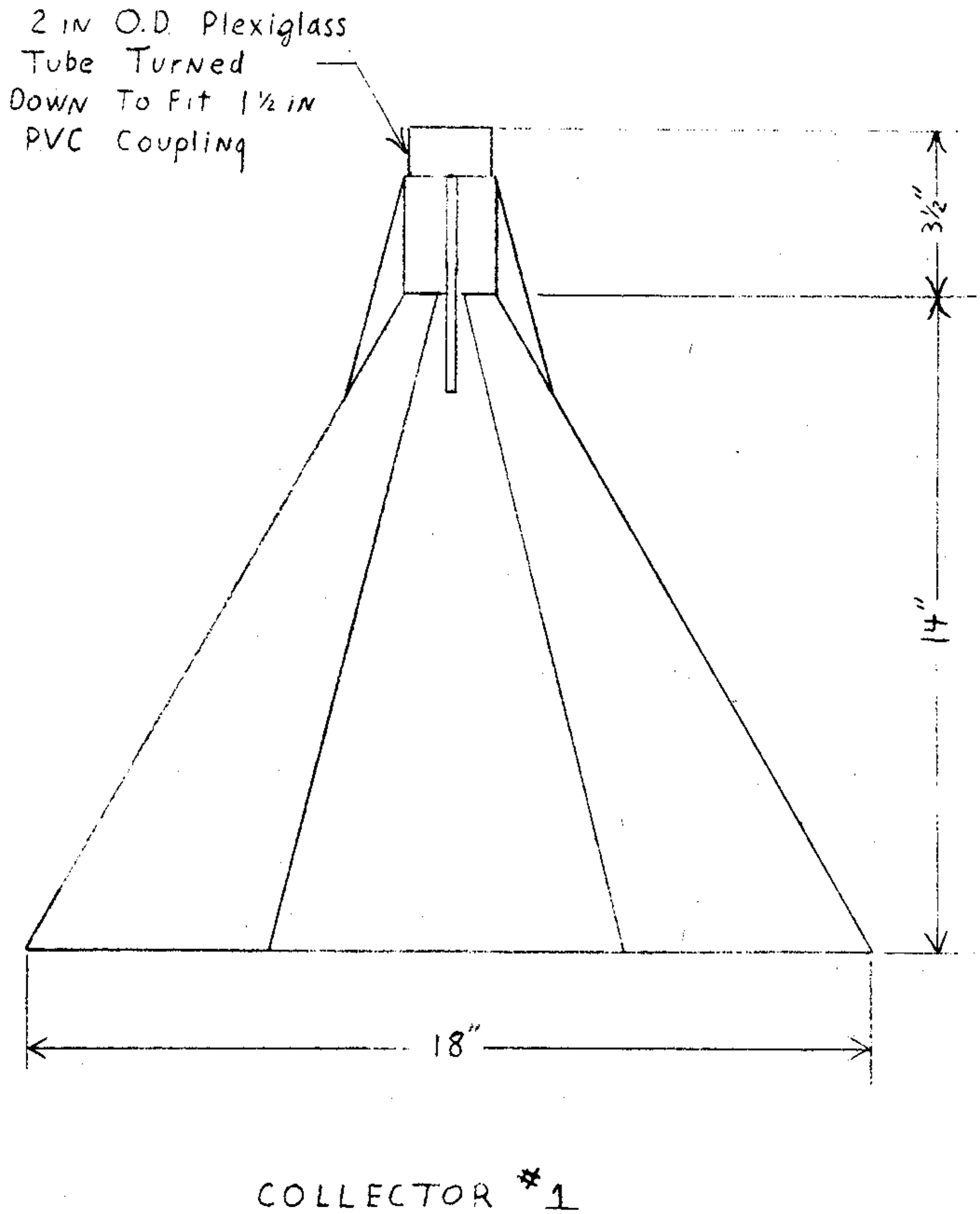
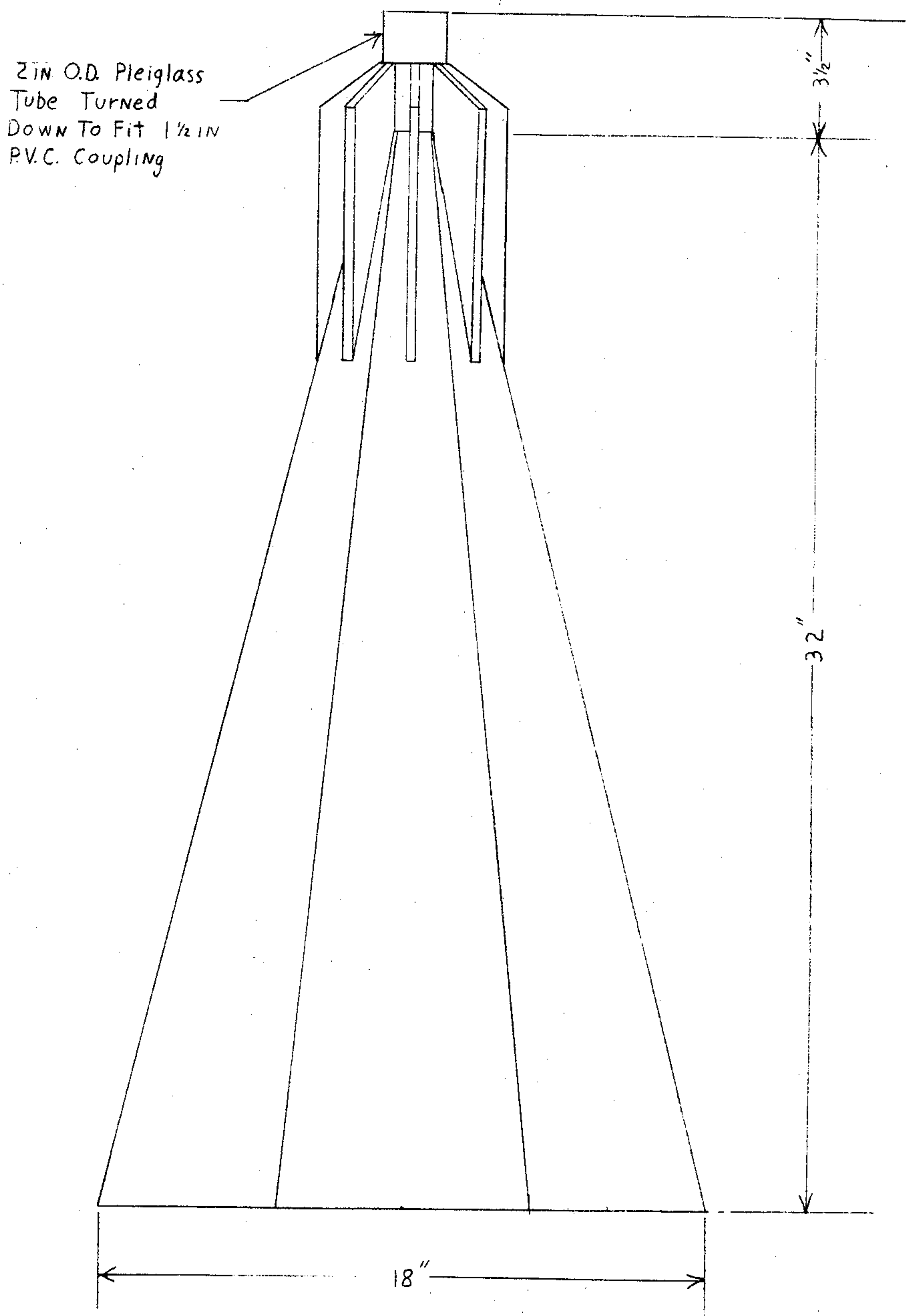
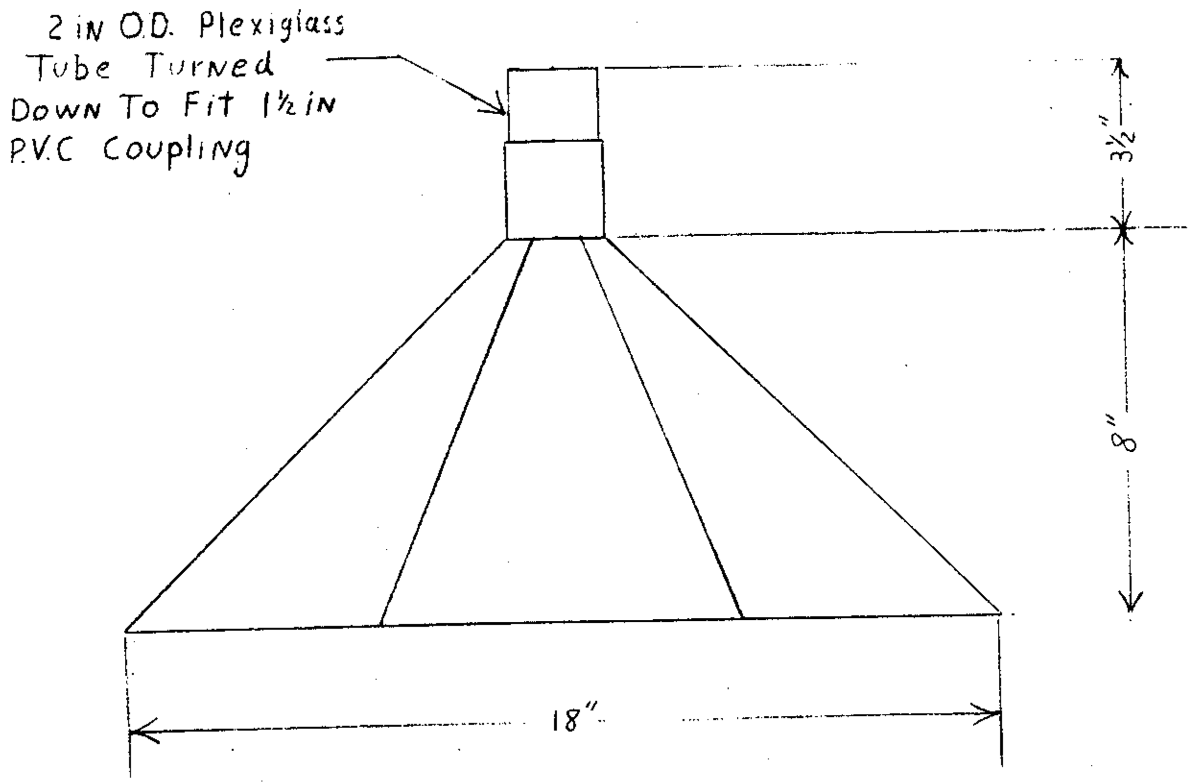

2 IN O.D. Plexiglass
Tube Turned
Down To Fit 1½ IN
PVC Coupling
3½"
14"
18"
COLLECTOR #1

Fig. 2a



COLLECTOR #2 Fig. 2b



COLLECTOR #3

Fig. 2c

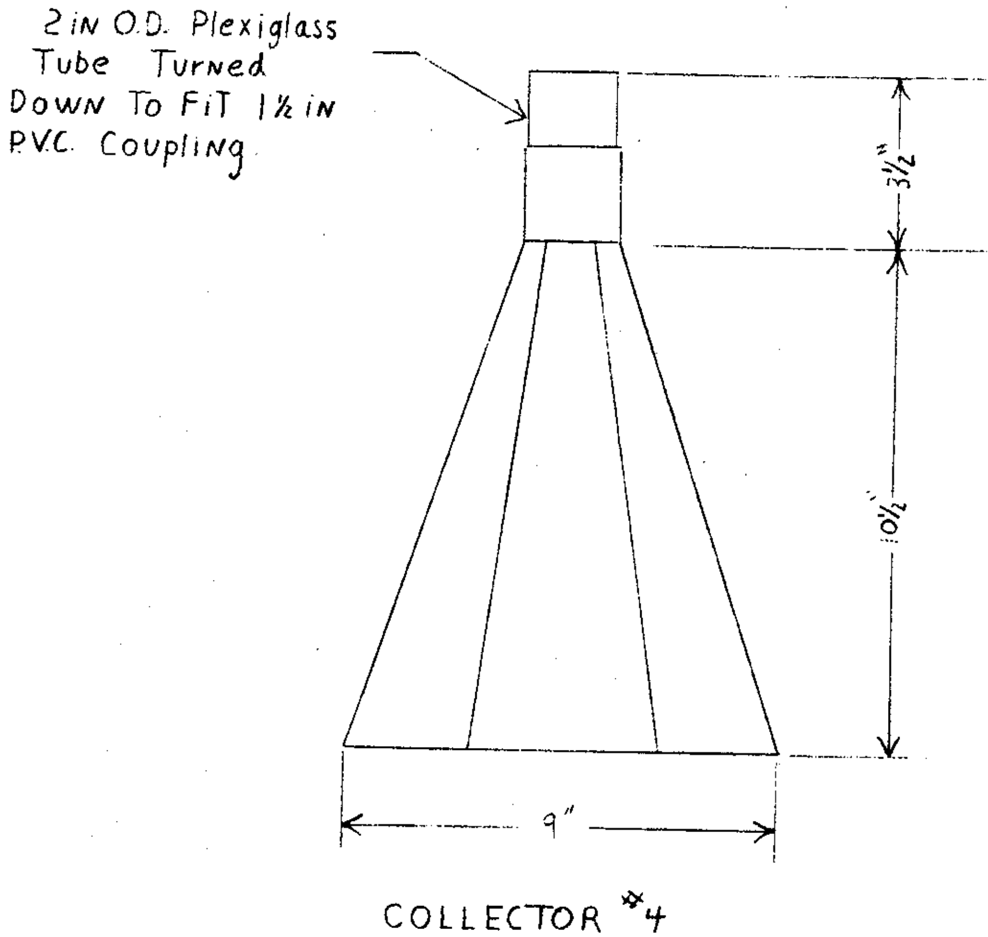

2 in O.D. Plexiglass
Tube Turned
Down To Fit 1½ in
P.V.C. Coupling
3½"
10½"
9"
COLLECTOR #4

Fig. 2d

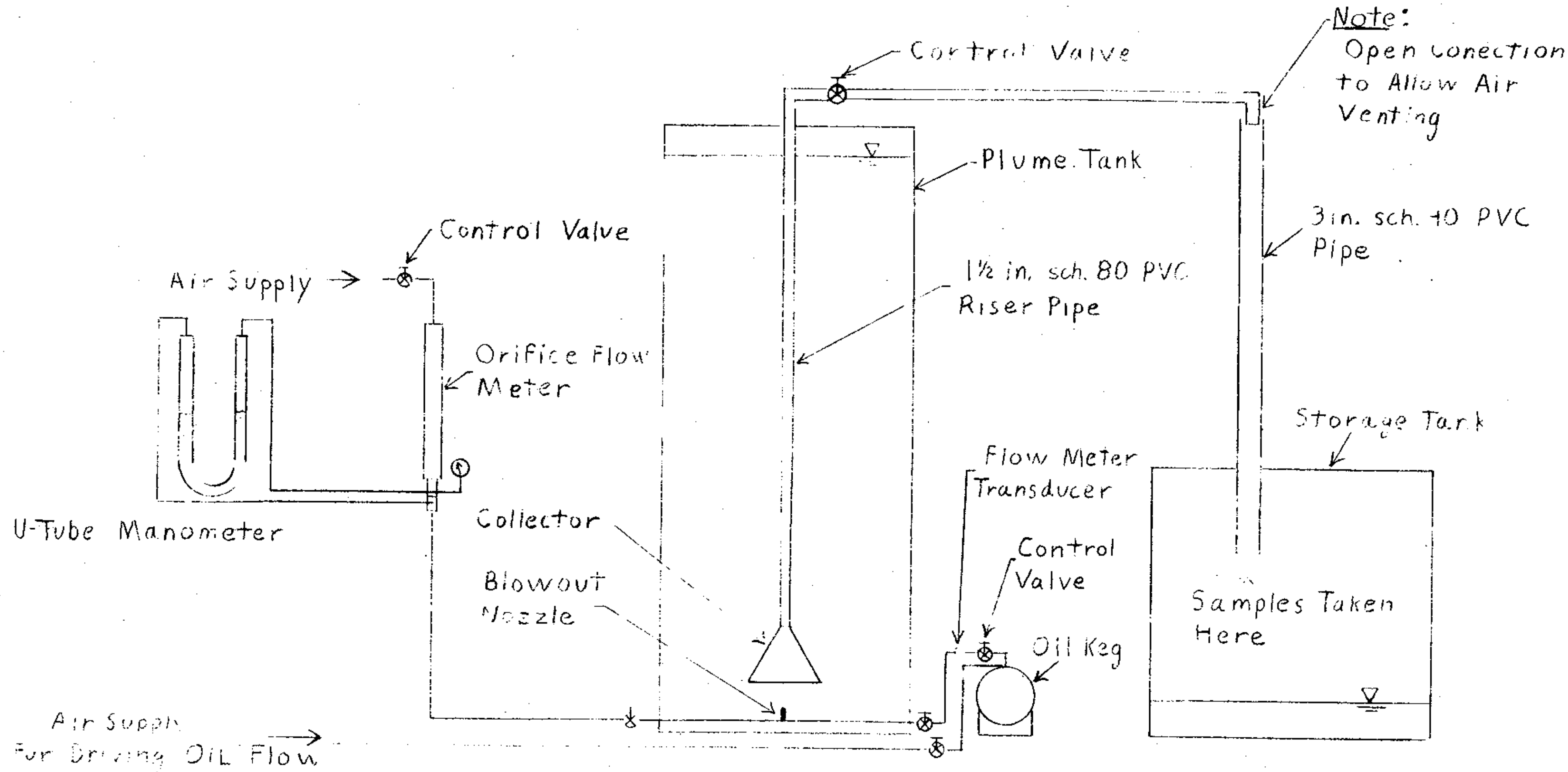


FIGURE 3. Schematic Arrangement of Experimental Apparatus

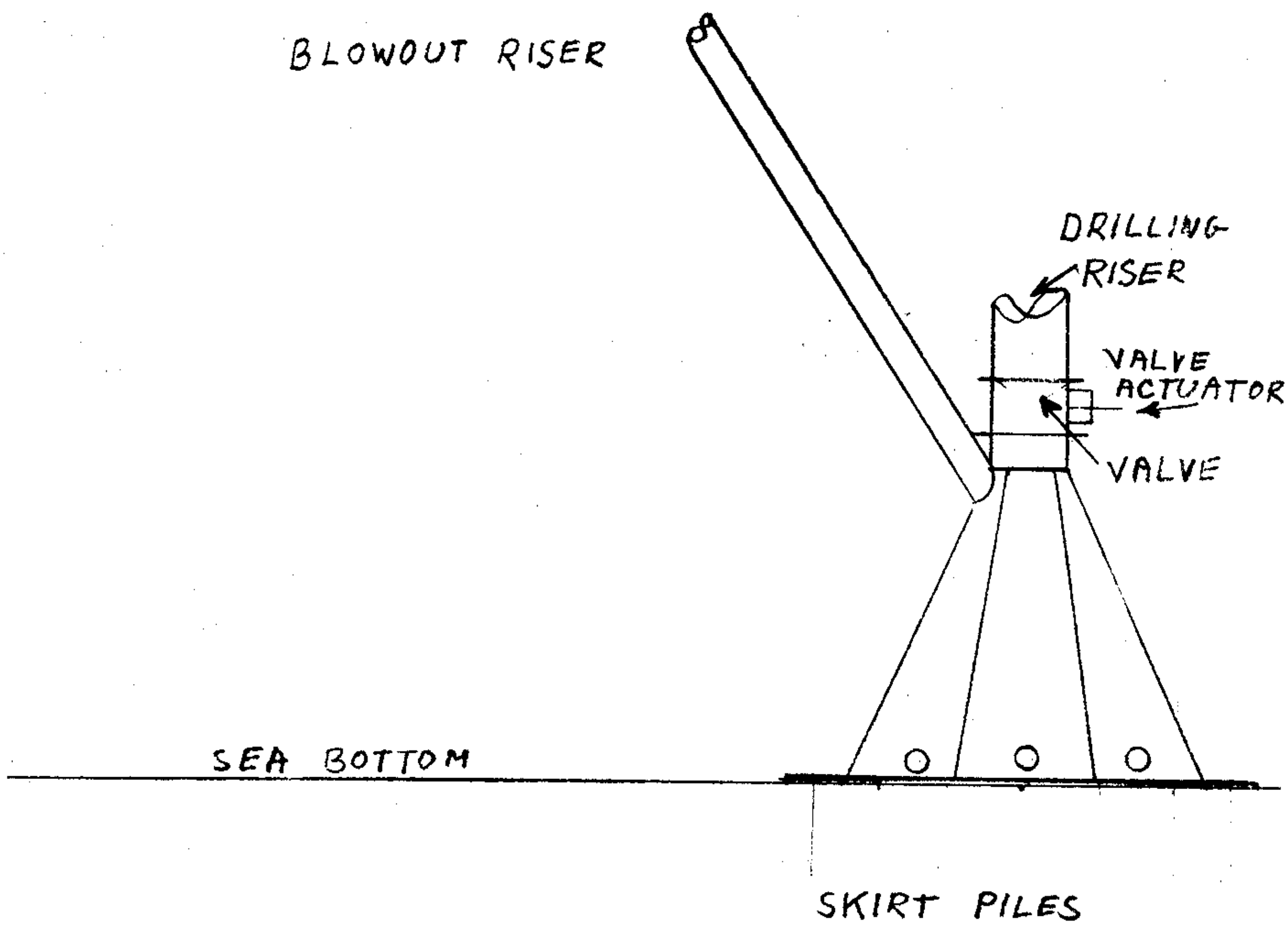


FIGURE 4. Concept for a Subsurface Collector Installed Before Drilling Begins

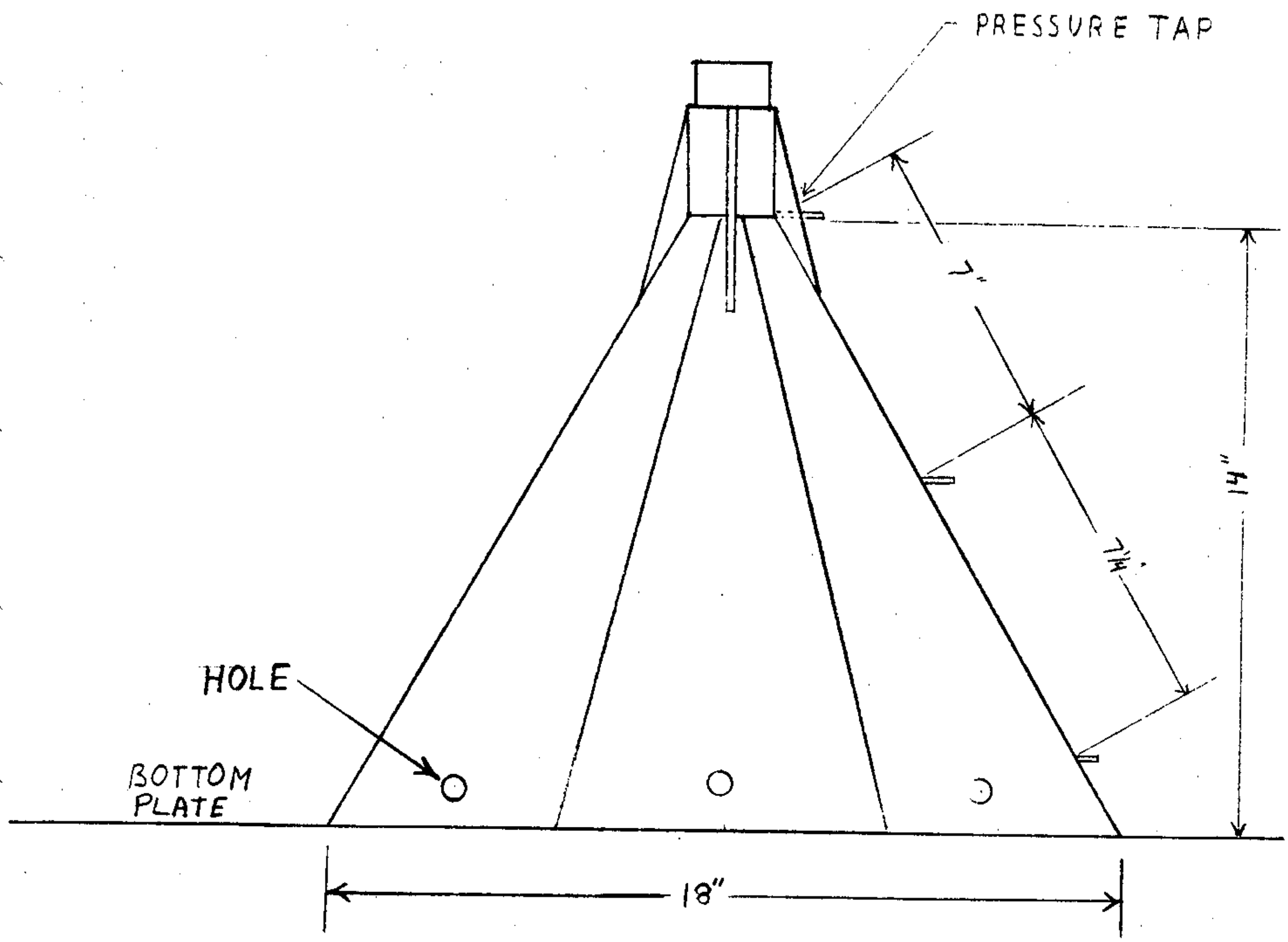


FIGURE 5. Model of the Bottom Mounted Subsurface Collector that was Tested

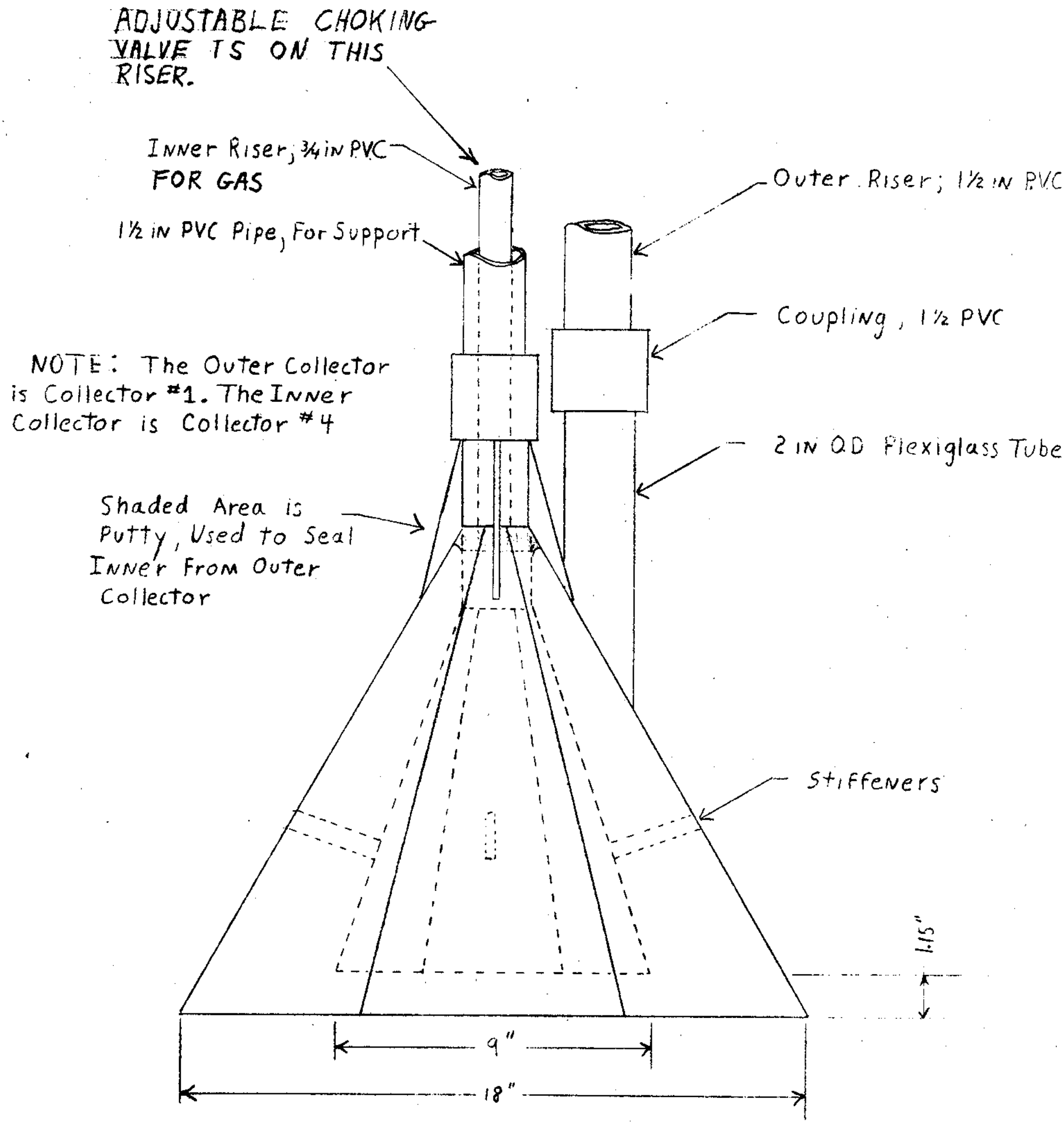


FIGURE 6. Gas Separating Collector.
By adjusting the choking valve on the inner riser, it is possible to obtain only gas through the inner riser and spill just enough gas from the inner collector into the outer collector to obtain maximum possible gas-lift pumping of liquid in the outer riser.

Fig. 7a Plot of % Oil Collected Vs. Total Collected Flow Rate for Collector #1.

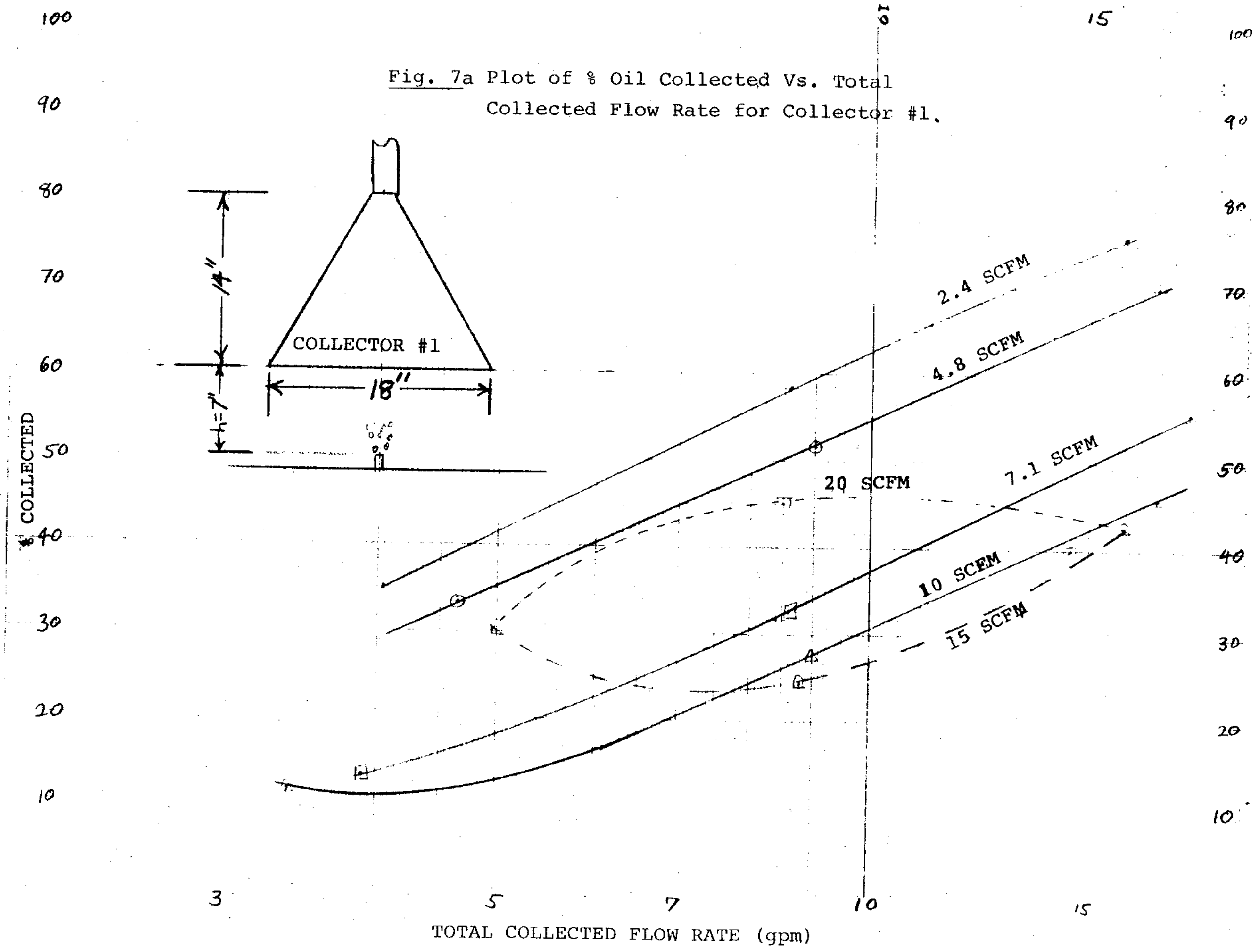


Fig. 7b % Oil Collected Vs. Total Collected Flow Rate for Collector #2

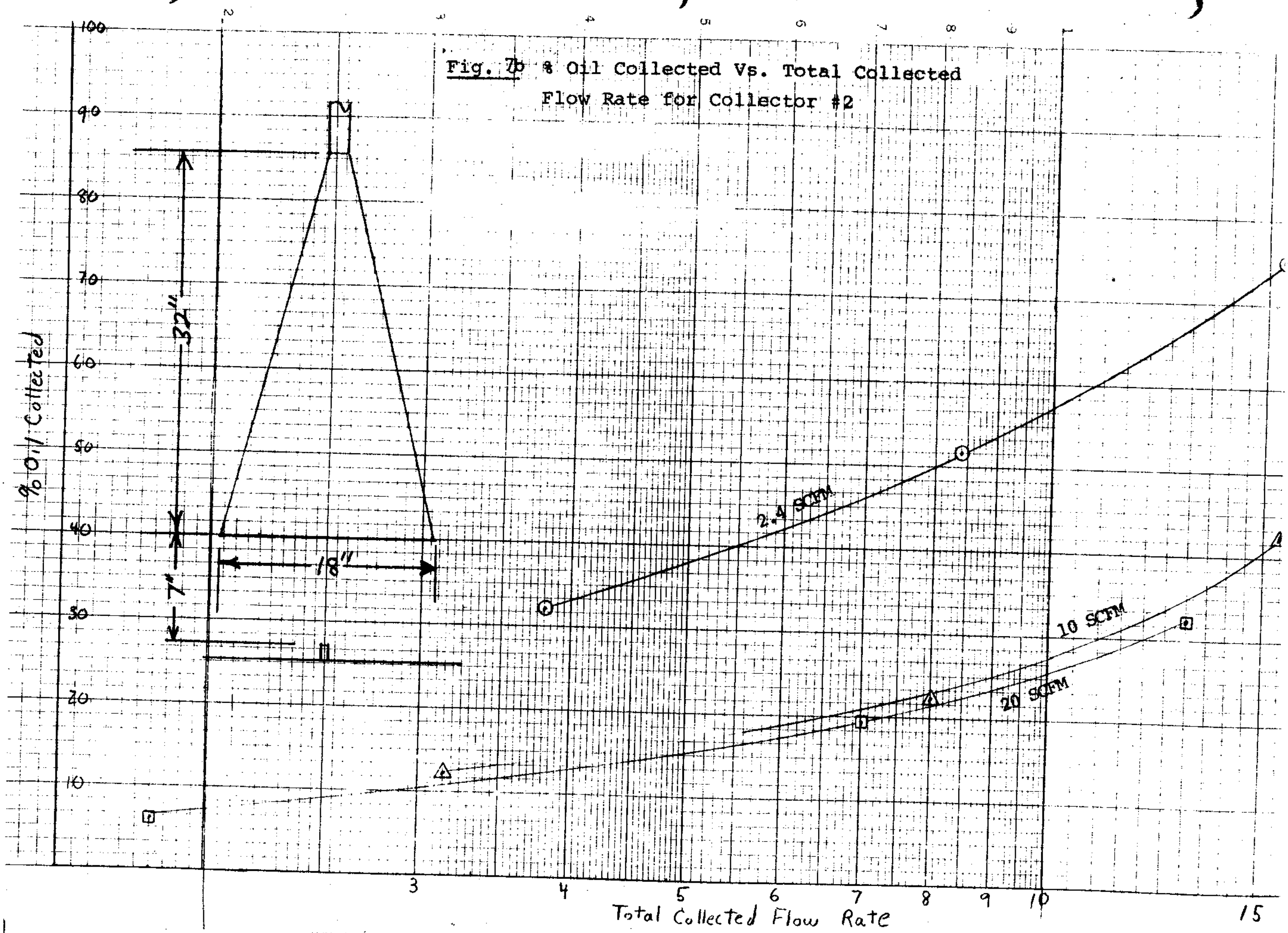


Fig. 7c % Oil Collected Vs. Total Collected Flow Rate for Collector #3

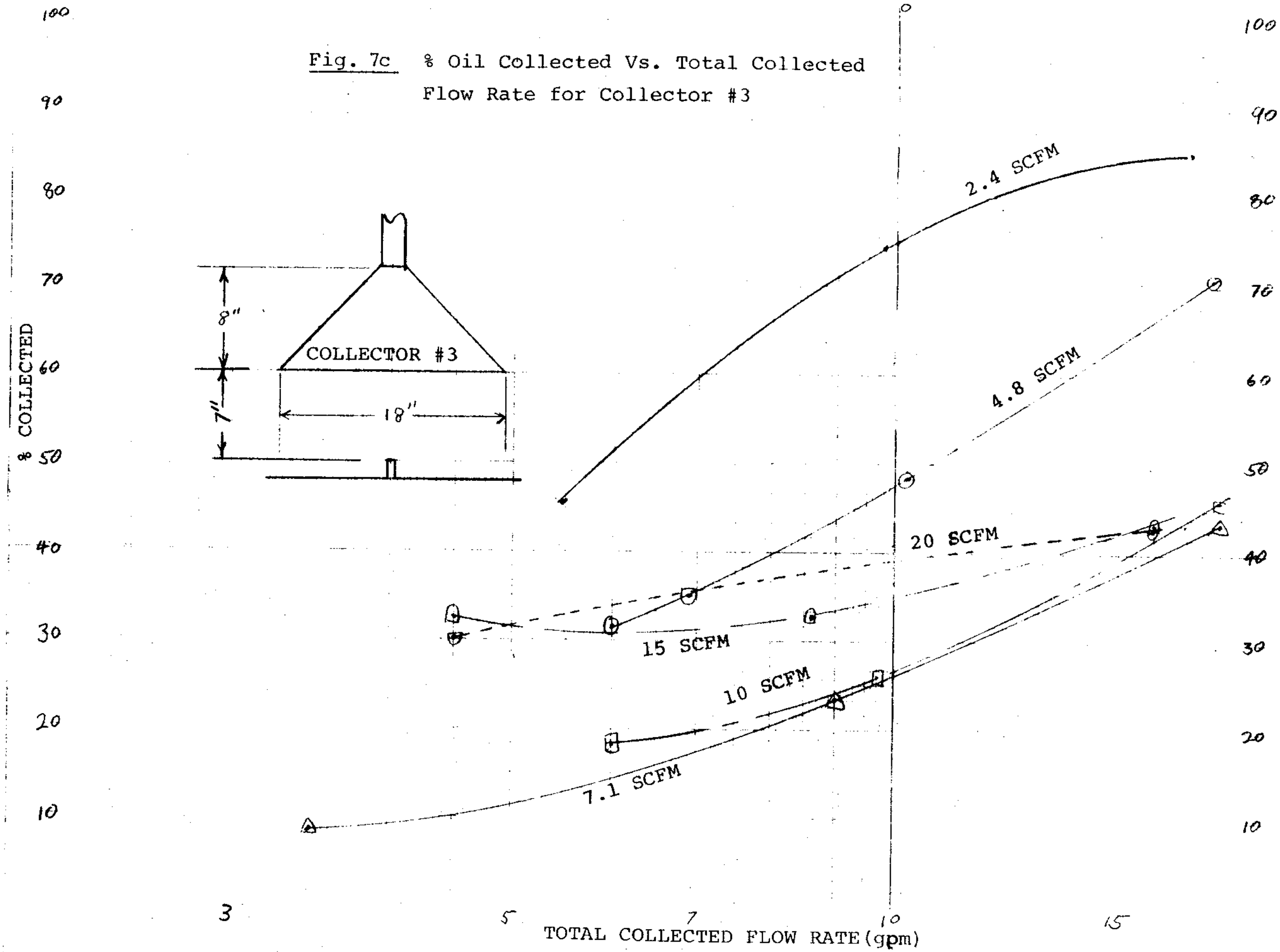
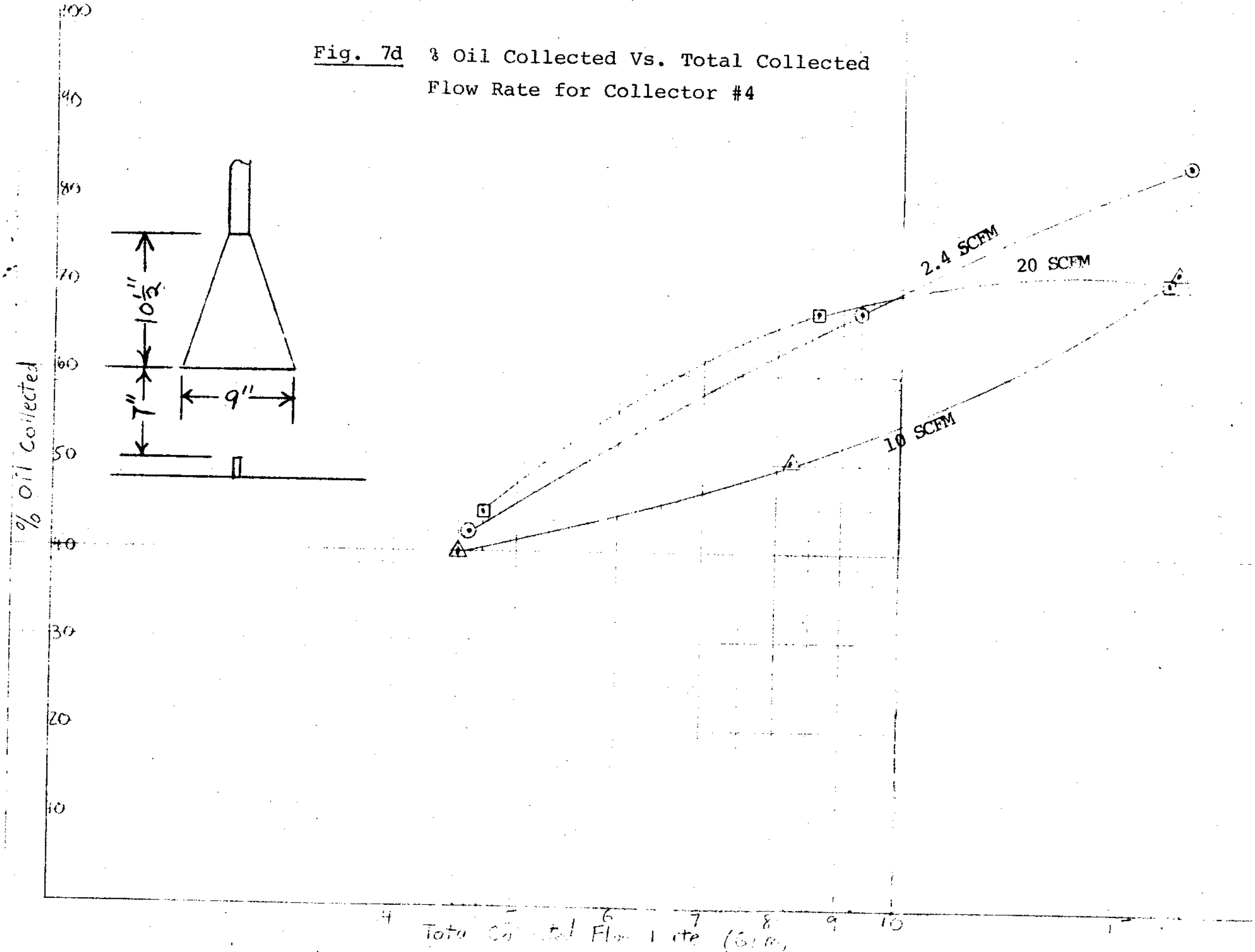


Fig. 7d % Oil Collected Vs. Total Collected Flow Rate for Collector #4



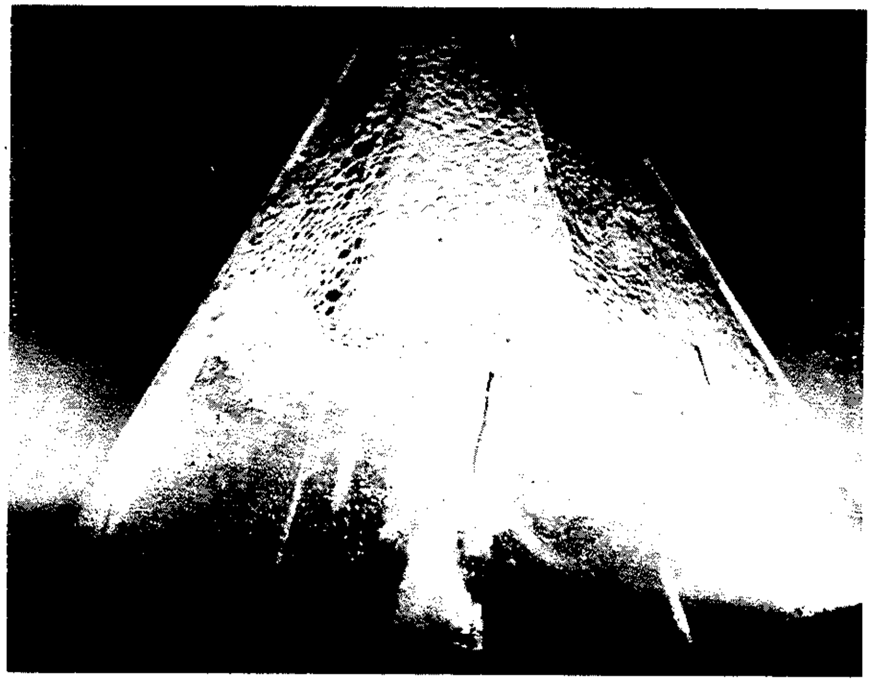
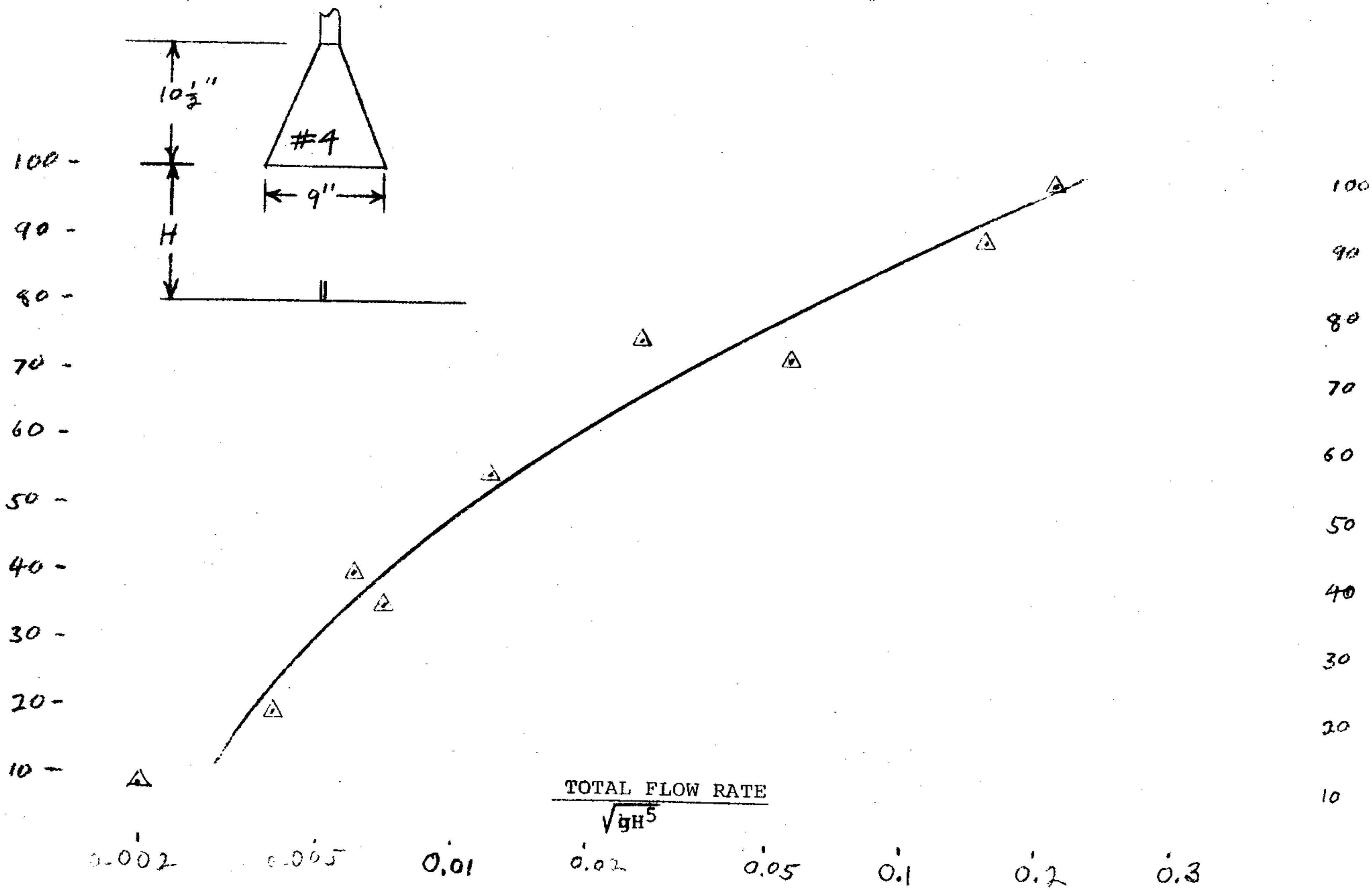


FIGURE 8. A Photograph of Collector Number One Operating in the Laboratory Plume Tank.

The bottom of the collector is 7" above the nozzle (model wellhead) which is delivering 7.1 SCFM of air. The plume itself can be seen entering the collector at the lower center. This plume is in a bubble flow zone. A mist flow zone exists above the bubble flow zone. In this zone the photograph shows the water droplets on the interior sides of the collector. The purpose of the yarns on the collector is to show the flow direction.

Fig. 9. % Oil Collected Vs. Froude Number for Collector #4



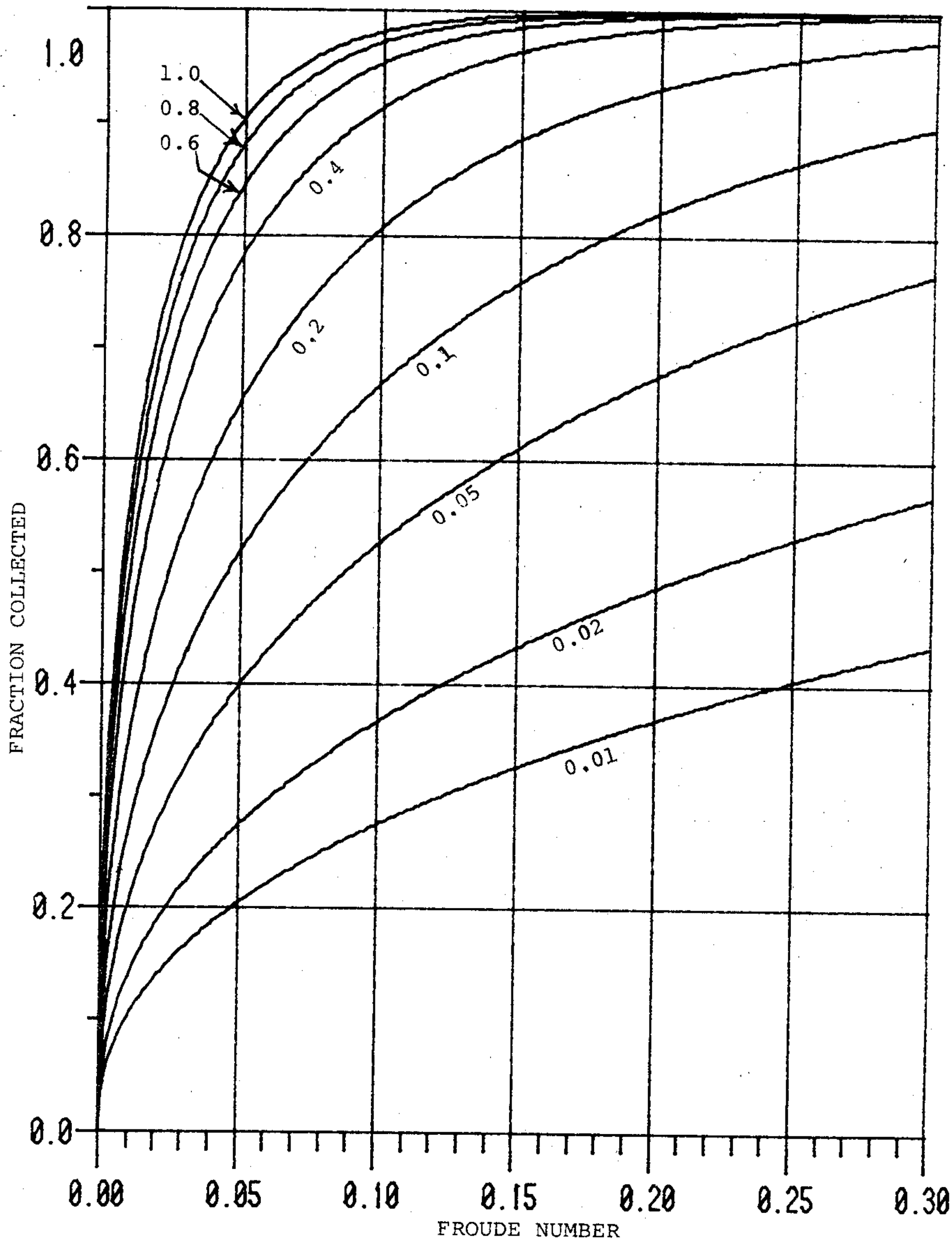


FIGURE 10. Curves of Fraction of Blowout Oil Collected vs Froude Number Obtained from Equations (2) and (3).

These equations serve to interpolate and extrapolate on the data. The number on each curve is the phase ratio, R.

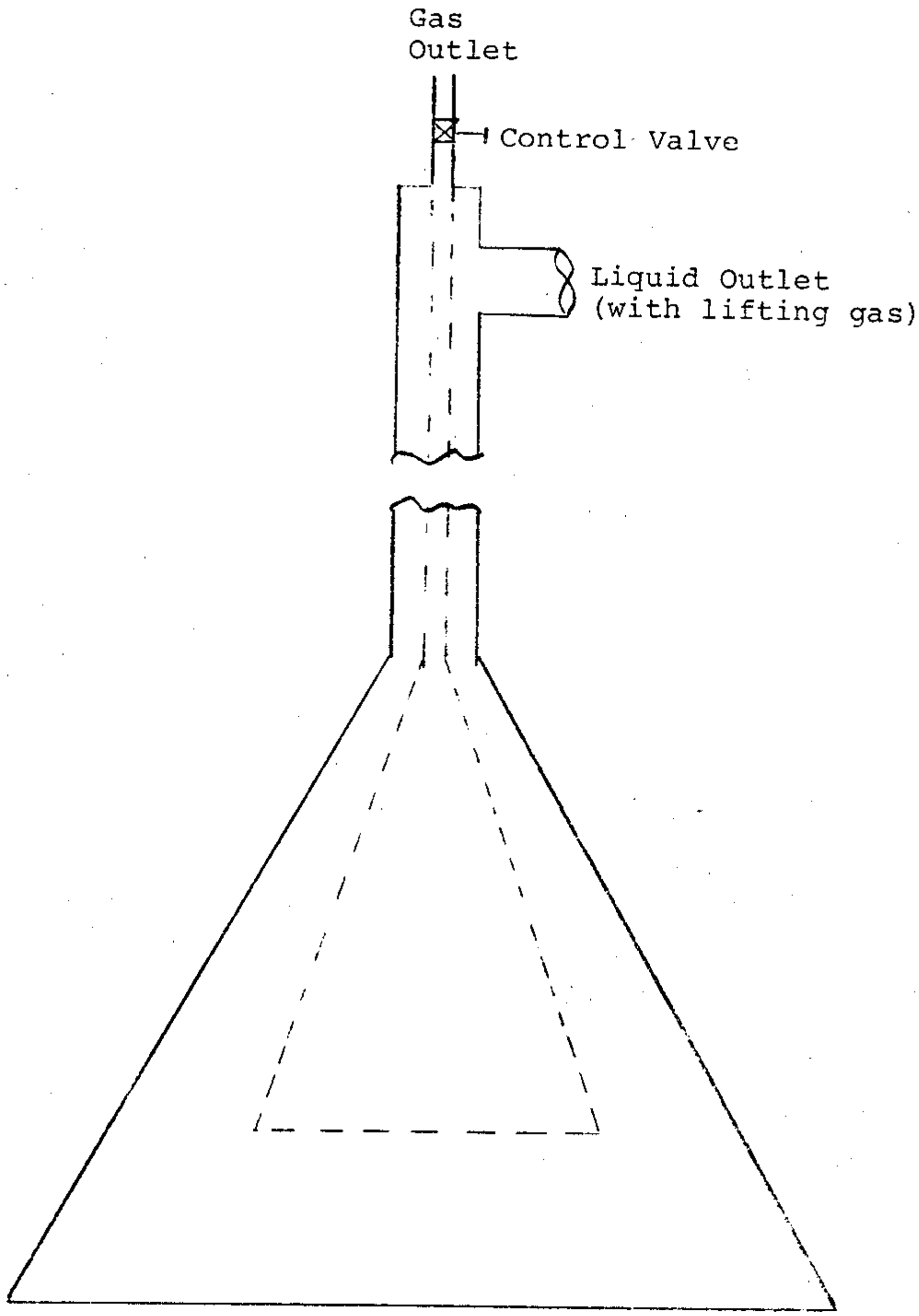


FIGURE 11. Concept for Separating Collector with Concentric Risers.

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1. Helwig, Jane T.,ed., SAS User's Guide, (SAS Institute,Inc., 1979).

2. Bill, Dr. James P., and Beggs, Dr. H. Dale, Two-Phase Flow in Pipes, 3rd edition, 4th printing, April 1979, (Dr. James P. Brill and Dr. H. Dale Beggs, 1978).