THE JET PUMP - A VERSATILE ARTIFICIAL LIFT SYSTEM

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Printed technical references to jet pumps can be traced as far back as 1852 England. However, consistent mathematical formulas were not published until 1933, when J. E. Gosline and M. P. O'Brien of the University of California at Berkley published *The Water Jet Pump*. In the same time period, the Jacuzzi Company received a patent for a jet pumping system that was successfully used to lift shallow water wells. Over the years, jet pumps have also been used as vacuum sources in applications such as steam ejectors on large, condensing steam turbines or on a wide variety of process industry vacuum requirements. Low to moderate lift water wells, and process and steam ejectors remain today as common industrial applications of jet pump technology. These applications, however, use liquid as a power source to move liquid, or gas as a power source to move gas. The initial problem in applying jet pumps to lift oil wells was based on the fact that a typical oil well contains a mixture of oil, water, and gas. The mathematical formulas of the 1930's did not produce accurate results in predicting pump performance and, consequently, required considerable modification. Also, jet pump performance calculations require a cycle of a number of repeat calculations, each one "zeroing in," as it were, more closely on the desired result. Making these calculations manually is very time consuming. It was not until the widespread availability of computers and the ability to properly program calculations of this type that the proper application of jet pump lift to oil wells became a practical reality. The first really successful applications were put in service in 1970. The use of this method of artificial lift has grown quite steadily since then.

It is not the intent of this paper to discuss in detail the theory of operation or the calculation methods employed to accurately predict jet pump performance. It is suggested that those interested in a detailed presentation of those topics refer to the 1987 edition of The Petroleum Engineering Handbook, published by the Society of Petroleum Engineers. Chapter 6 of this publication, authored by Hal Petrie of National-Oilwell, contains a wealth of excellent information on hydraulic pumping, including both jet and reciprocating pumps. However, in order to discuss the versatility of jet pumping oil wells, a basic discussion of the Hydraulic Lift System and the jet pump's design characteristics is in order, since these are the basis of the jet pump's versatility.

Figure 1.0 is an example of a typical, single well, hydraulic power unit, operating with a single tubing string, "casing free" well completion. This is the most common Hydraulic Lift System using either a reciprocating or jet pump. In this arrangement, total well returns, consisting of produced fluid (oil and water) and gas, along with exhaust power fluid are all brought from the well casing annulus to the reservoir vessel.

This vessel has a normal working pressure in the 155 PSI range. The free gas, at vessel operating pressure, is discharged to the flow line while maintaining a gas cap in the vessel. The system is maintained at a pressure typically 10 to 15 PSI above the flow line by the back pressure control valve. The oil and water form a rough separation in the vessel and the appropriate fluid is drawn off for power fluid, either oil or water. In most domestic USA wells, water cut is over 25 percent and, consequently, the majority of jet pumps on those systems are operated using power water. Valving on the vessel is arranged to provide for power oil or water. With the multiplex pump suction low in the vessel and flow line outlet high in the vessel, water will tend to accumulate in the vessel and water will become the power fluid. The power fluid passes through a cyclone desander to remove solids prior to entering the multiplex pump suction. Appropriate differential pressure is maintained across the cyclone, in this case by a gear type charge pump, shaft driven off the multiplex pump, and differential pressure control valves. Cleaned power fluid is taken off the top of the cyclone, and dirty fluid off the bottom is returned to the bottom of the vessel and ultimately to the flow line. The multiplex pump, driven by an electric motor, natural gas engine, or in some cases a diesel engine, raises the power fluid to the required operating pressure, typically in the 2500 to 4500 PSI range. With a jet pump system, a pressure controller is used to maintain constant operating pressure and excess power fluid is bypassed back to the vessel. Once the operating system is stabilized, power fluid in the required quantity is recirculated and the well production of oil, water, and gas is discharged from the vessel into the flow line and on to the treating and separating facilities. A variation of this unit is a dual vessel system. In this arrangement, total well returns are brought first to a vertical accumulator vessel. There is no charge pump in this system. The cyclone is located between the vertical accumulator and the horizontal reservoir. A differential pressure valve maintains the accumulator at a higher pressure than the reservoir to drive the fluid over the cyclone and clean the power fluid. Basic operation is the same - required power fluid recirculated and well production directed to the flow line.

The downhole completion of the system consists of the pump bottomhole assembly, run in on the single tubing string and set, typically, just above the well perforation on a single hole packer. The "free type" jet pump operates inside the tubing and the bottomhole assembly. This feature allows the jet pump to be circulated into the well hydraulically for operation and out of the well for maintenance without pulling tubing. This is accomplished using the wellhead control valve to direct power fluid down the tubing and up the annulus for operation, and the reverse for "pump-out." In this arrangement, entire well production - oil, water, and gas - is brought through the jet pump and discharged into the casing annulus on the top side of the packer. Exhaust power fluid is commingled with the well production and the total mixture lifted to the surface.

Figure 2.0 is a schematic diagram of a jet pump, located in its bottomhole assembly, and in the operating mode. High pressure power fluid from the surface unit is forced through the jet pump nozzle, where the fluid stream is reduced in diameter and its velocity greatly increased. This high velocity jet stream passes through a small open space in the pump between the nozzle and the throat. Well fluid, driven by formation pressure, flows into this space through side ports in the pump.

The jet stream of power fluid entrains the produced fluid and drives it into the pump throat. Pressure rises in the produced fluid through energy transfer from the power fluid, during the turbulent mixing process which occurs in the straight bore of the throat. The combined stream of power fluid and produced fluid passes through the throat and into the diffuser section of the pump. In this diffuser section, the velocity head is converted to additional pressure to lift the mixture of exhaust power fluid and produced fluid to the surface.

Now that we have reviewed the operation of the Hydraulic Lift System power unit and the jet pump, we will examine the construction characteristics of the jet pump itself. It is those characteristics that have provided for the development of jet pumping into a highly versatile type of artificial lift system.

1. No Moving Parts - This is likely the most significant characteristic of the jet pump since it is the basis for a number of adaptations that expand the versatility of application. In itself, this characteristic provides significantly extended run time between any required pump maintenance. There are no contact surfaces to wear or gall and no abrasive damage caused by solids trapped between moving parts.

    a. Corrosion Resistant Materials - Without the potential for galling inherent in moving parts, the jet pump can quite easily be manufactured from a variety of corrosion resistant alloys. This allows the jet pump to operate with good performance results in highly corrosive conditions.

    b. Can Handle High Sand Cut - In addition to no moving parts, the jet pump nozzle and the throat liner are typically manufactured from various grades of precision machined carbide. The use of this highly abrasion resistant material in the high velocity areas of the jet pump allows it to successfully handle far greater solids load than either centrifugal or reciprocating pumps can tolerate.

    c. Can Handle High Gas/Oil Ratios - Significant free gas volumes can be handled without the mechanical problems of pounding or gas lock associated with positive displacement pumps or the suction side choking possible with centrifugal pumps.

    d. Can Handle High Bottomhole Temperatures - With no moving parts requiring any type of lubrication, and a minimum number of nonmetallic components, jet pumps can operate successfully in temperatures approaching 400° F. with only minimal modification.

2. "Free Type" Pump Design - The pump is put into operation or retrieved for maintenance by hydraulically circulating it in and out of the well. This characteristic completely eliminates the need for a pulling unit for routine maintenance, significantly reducing both cost and total down time.

    a. Available in models designed to operate in 1-1/2 inch, 2 inch, 2-1/2 inch, and 3 inch tubing installations.

b. Subsurface pressure recorder is easily attached to the jet pump and run into the well with it.

The lack of vibration resulting from no moving parts allows the recorder to perform more accurately and without mechanical damage. Using this tool provides accurate bottomhole pressure at different flow rates and produces a "current" PI curve for the well at minimal expense.

3. Wide Operating Range - With four sizes of pumps, 16 nozzle and 18 throat sizes, total produced fluid can be a low as 100 BPD or even less, up to over 12,000 BPD.

   a. In a given pump size with a given nozzle and throat combination, production rate can be changed by changing the surface power fluid pressure.

   b. In a given pump size, nozzle and throat combinations can easily and quickly be changed to maximize system performance as well conditions change over time.

4. Available in Sliding Sleeve Models - Can be operated in standard sliding sleeve seal bore diameters from 1.875 to 4.562 inches and seal pitch lengths of 19.66 inches or more.

   a. Can be supplied for production applications or high volume drill stem testing - "Conventional or Reverse Flow."

   b. While sliding sleeve models are not "free type" pumps, they are run in and removed on standard wire line equipment so no "big rig" is required for routine servicing.

5. Compact, Lightweight, and Easy To Handle - Most jet pumps are small enough to be easily handled by one man. The 3 inch Hi Volume Jet, for example, has a nominal rating of 12,000 BPD, yet is less than 3 inches in diameter, approximately 60 inches overall length, with the swab nose attached, and weighs about 75 pounds.

INSTALLATION EXAMPLES

The following are examples of actual jet pump installations around the world, illustrating the jet pump's versatility in being able to successfully solve a variety of artificial lift problems:

1A. Extremely Remote Location, Severely Limited Facilities in the Jungle of Northern Indonesia (Borneo) -- Initially, six wells were put on jet pump. The location was so remote that the first six systems, including the surface power units, were supplied in small module construction, limited to a maximum weight of 4,000 pounds each. This was done to allow helicopter lift of all surface and subsurface equipment to each well location. Due to very marshy conditions, reinforced well pads were constructed at each location to support a helipad and all required surface equipment. Individual well pads and the central flow station were connected by a system of boardwalks, built to accommodate pedestrian and bicycle traffic only.

The production tubing and downhole completion equipment were installed using a heli-rig, which was then removed from the field. Formation gas was inadequate for gas lift, there was no field wide electric power system, and the marshy conditions eliminated the use of any pulling unit. The inherent low maintenance characteristic of jet pumps, plus the elimination of any pulling unit for routine maintenance due to the "free pump" design were primary considerations in selecting hydraulic jet pumps for this installation. Surface units are powered by multicylinder natural gas engines. Formation gas is available in adequate supply for this purpose. The high degree of success of this installation is indicated by a number of repeat orders for additional units for this field as other wells required artificial lift.

1B. Remote Location, High Sand Cut - the Australian "Outback" of Western Queensland and North Eastern South Australia -- The Cooper/Eromanga Basins in this region are barren desert, 1000 miles or more from metropolitan areas. In a number of cases, the fields are worked from a company village with two complete crews, flown to and from the village, alternating on and off, similar to far offshore platforms in the Gulf of Mexico or the North Sea. There are roads to the interior, but most are not hard surfaced, making logistics somewhat difficult. One of the earliest jet pump installations replaced a large bore tubing pump/beam unit. The most significant production problem was very high sand cut in the produced fluid, resulting in extremely short life on the tubing pump. Down time and expense were very high. Waiting and paying for pulling units were major contributors to the expense. A jet pump lift system was installed, and the initial pump throat operated satisfactorily for approximately ten months before the pump had to be circulated out of the well for maintenance. This success results in a significant number of additional jet pump system installations in this remote "Outback."

2. High Bottomhole Temperature -- A steam flood with 26 jet pump lift systems was installed in Southern Louisiana in 1987. Operating bottomhole temperatures during the flood were in the area of 350° F. The downhole bottomhole assemblies and jet pumps are essentially standard equipment, but Viton "O" rings were used in place of the standard Buna "N" for temperature reasons. Because this formation proved to be highly fractured, making it somewhat difficult to properly flood the formation, steam flooding was discontinued after approximately four years of operation. The 26 jet pump systems, however, are still in operation and several additional wells in the field have been converted to jet pump lift. During the four years of steam flooding, there were no appreciable problems with the downhole equipment caused by the 350° F. well bore temperature.

3. High Corrosion -- The standard jet pump materials of construction offer a reasonably high degree of corrosion resistance and perform well in many applications. For particularly corrosive conditions, however, there are additional alloys available which have been used very successfully.

3A. CO_2 Flood -- For applications in these areas, such as West Texas and Southeast New Mexico, a good many jet pump lift systems have performed well. Bottomhole assemblies and jet pumps using 316 Stainless Steel for the tubular portions and Nitronic 50 and Nitronic 60 for crossovers, connectors, etc., have proven to be highly effective in resisting this type of corrosion.

The Nitronic alloys are stronger than 316 Stainless Steel, but they approach it in corrosion resistant characteristics. In addition, they have a greater resistance to galling, which, along with specialized thread lubricants currently available, makes for easier assembly and disassembly.

3B. High Chloride Concentrations -- A number of fields in North Dakota and elsewhere exhibit this problem. The solution has been jet pump lift systems with bottomhole assemblies and jet pumps also utilizing Nitronic 50 and Nitronic 60. The tubular sections, however, in these applications have used L-80 tubing, 9 Chrome, 1 Moly, with a high degree of success.

3C. An Offshore Platform with a Particular Corrosion Problem -- A major independent is operating an offshore platform in Abu Dhabi. There is a significant H_2S problem compounded by the fact that the platform has no permanent rig. Any pulling requirement is extremely expensive. Four jet pump lift systems were installed using particular alloys to provide the best available corrosion resistance to avoid any frequent pulling requirements. In this instance, bottomhole assemblies and jet pumps were constructed of a combination of 17-4 pH Stainless Steel and Inconel Grades 625 and 718. This platform has been on production for approximately two years and the bottomhole assemblies have not required maintenance. The jet pumps operate below subsurface safety valves which eliminates the ability to circulate the pumps out of the well for maintenance. They are, however, easily retrieved without a rig by using a standard, on board, wire line unit and standard Otis GS type fishing necks mounted on the top of the pumps.

4. High Volume -- Jet pumps can easily handle volumes that are beyond practical limits of reciprocating pumps. Jet pumps designed to operate in 3 inch tubing have successfully lifted volumes in excess of 10,000 BPD. Although this pump has a nominal rating of 12,000 BPD, under favorable well conditions, one installation in Tunisia exceeded 15,000 BPD.

5. Sliding Sleeve Jet Pumps -- Jet pumps have been successfully adapted to operate in downhole sliding sleeve assemblies with seal bore diameters from 1.875 to 4.562 inches. These pumps have a seal pitch length as short as 19.66 inches and, consequently, can be adapted to operate in a number of different manufacturers' sliding sleeve assemblies. There are two current type applications for these pumps, production and drill stem testing. Production units are commonly arranged for "conventional" flow, power fluid down the tubing and production up the annulus. There are applications of this type in operation in Cook Inlet, Alaska, New Zealand, and elsewhere.

Drill stem test units are commonly arranged for "reverse flow," power fluid down the annulus and production up the tubing. Figure 3 shows the drill stem test, "reverse flow" arrangement. With the sliding sleeve in the "open" position, the pump is run in on standard wire line tools. The two seal stacks on the pump enter the top and bottom seal bores and the top lock, provided by the sliding sleeve manufacturer, positions and holds the jet pump in place.

6. Lifting Low Gravity, "Heavy Crude" -- Several installations, plus a specific field test conducted in Wyoming in 1985 with a major operator, have substantiated jet pumps as a viable method of lifting heavy crude. When water is used as power fluid, resulting in a water cut on the combined produced fluid and exhaust power fluid of more than 10 percent, the jet pump performs essentially as if it were pumping water. This results in considerably better efficiency for a jet pump lifting heavy crude, than for an electric submersible pump, due to the friction drag through the ESP. With viscosity of 200 CP, we would anticipate the jet pump to have an efficiency advantage of approximately 50% over an ESP. Figure 4 shows a jet pump installation, lifting moderately heavy crude (16° API) on an offshore platform in Southern California. It is desirable to keep both the produced fluid and the power fluid off the casing annulus. This eliminates any elevated operating pressure on the well casing. It also retains the heavy crude in the well tubing, removed from the casing annulus where some "chilling" effect would occur in the riser from the sea floor to ocean surface level, in particular. Again, exhibiting the versatility of the jet pump lifting system, a high volume pump to provide maximum fluid passages, particularly on the pump intake side, was adapted for "reverse flow." The bottomhole assembly was modified to provide a landing collar, side string, and power fluid shoe. Power fluid side string tubing is stabbed into the landing collar, using a landing spear. Power fluid is provided down this side string and produced fluid and exhaust power fluid is lifted up the main tubing string. This "parallel free" downhole completion does not require a packer. Consequently, any gas is vented up the annulus. This particular pump, being required to clear the I.D. of a subsurface safety valve, is not circulated out of the well. It is, however, easily removed for maintenance using a standard wire line unit. Friction holddown rings are installed on the bottom of the pump. These rings prevent the pump from being lifted out of the bottomhole assembly during start-up when there is inadequate static pressure in the production tubing to hold the pump in place.

7. Operation with a Downhole Pressure Recorder -- See Figure 5. A pressure recorder tool can easily be mounted on a jet pump and circulated into the well in the normal manner. The tool allows the pressure recorder to read pump intake pressure. Varying the system's operating pressure at the surface will vary the jet pump's lifting production rate. By operating at three different pressure rates, and recording actual production at those rates, a "current" PI curve for the well can be generated. This can be done over a period of just a few days and at very reasonable expense. Analysis of this data allows recalculation of the jet pump performance and possible change of nozzle and throat size to maximize system output. The jet pump recorder tool will accommodate downhole pressure recorders of several different manufacturers.

8. Concentric, Inside the Tubing Production -- Figure 6 shows a small diameter jet pump run in on coil tubing or "slim line" coupled tubing. A standard rod pump seating assembly is attached to the bottom of the jet pump and is landed in a tubing seating nipple. Power fluid is brought down the coil tubing (1-1/4 inch, for example). Produced fluid and exhaust power fluid is lifted up the tubing annulus between the 1-1/4 inch and the 3 inch tubing string. This type of adaptation could be used for dewatering gas wells, lifting heavy crude in a "huff and puff" steam operation, etc.

9. Application to Horizontal Wells, Current and Future Potential -- Figure 7 is a schematic of a typical horizontal well completion. Jet pumps have been, and continue to be, successfully used to lift horizontal wells. Currently, most horizontal wells are completed as "open hole" in the horizontal section or have a slotted liner installed in that section. Very few are currently completed with solid casing to the end of the horizontal reach. This type completion (open hole or slotted liner) effectively eliminates installing a packer in the horizontal section. Consequently, jet pumps lifting horizontal wells are currently "set" in the vertical well bore or part way down the radius section. This is also currently the most common pump location for other types of artificial lift systems. However, when horizontal well completion techniques improve, as it is generally believed they will, placing a packer in the horizontal section will become more practical. This ability is most important as it will provide for practical methods of remedial well work, such as acidizing and fracturing. When this technology becomes available, it will be possible to set a jet pump in the horizontal section, on a packer, "above" the last row of perforations. Having no moving parts, there will be no "gravity induced" wear patterns in the pump. A number of current, standard design configurations of jet pumps and bottomhole assemblies are short enough to easily pass the well's radius section without difficulty. This pump location will provide several hundred pounds of additional pump intake pressure, thereby increasing the overall efficiency of the jet pump lifting system.

SUMMARY

In its relatively short history of 22 years in oilfield service, the modern jet pump has evolved into a highly versatile artificial lift system. As downhole completion and other areas of production technology continue to advance, the basic design characteristics of the jet pump will allow for continued evolution of its wide range of artificial lift applications.

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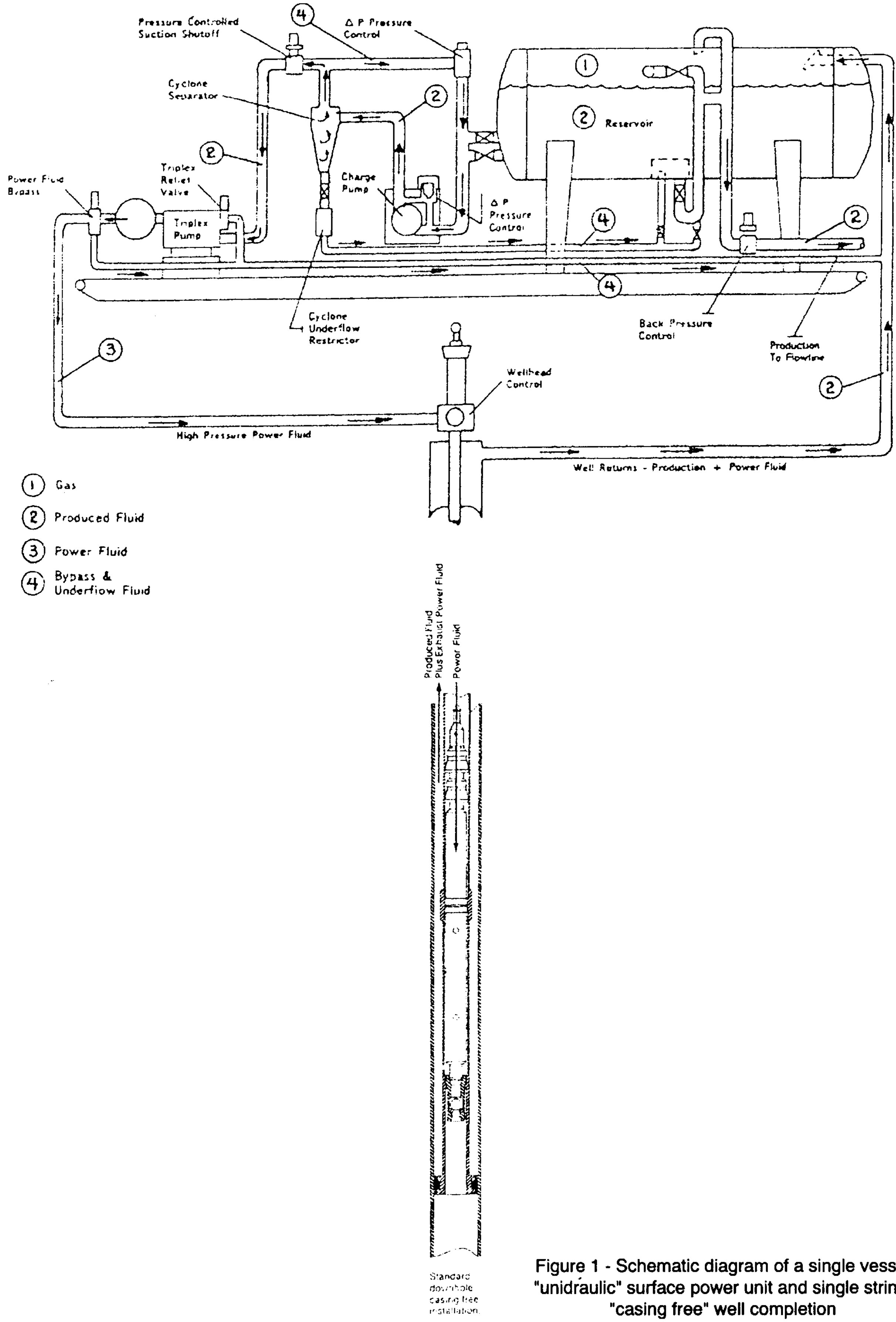

Figure 1 - Schematic diagram of a single vessel "unidraulic" surface power unit and single string, "casing free" well completion

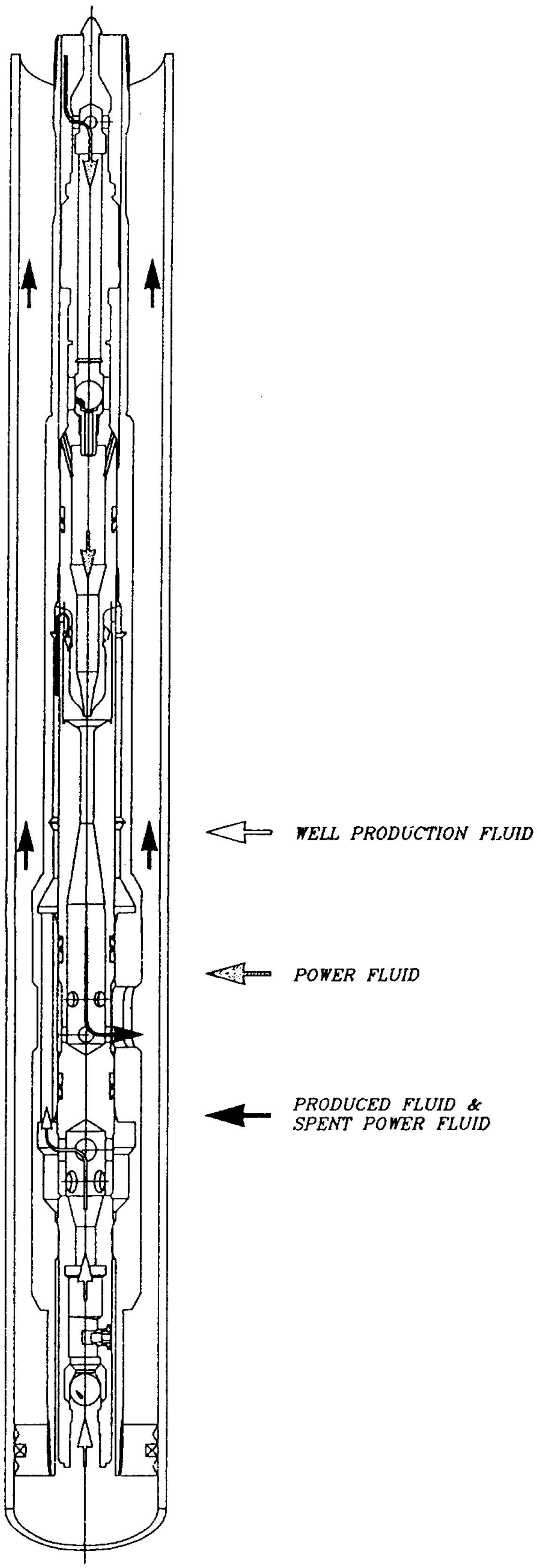

Figure 2 - High volume jet pump with bottom hole assembly for single tubing string, "casing free" completion

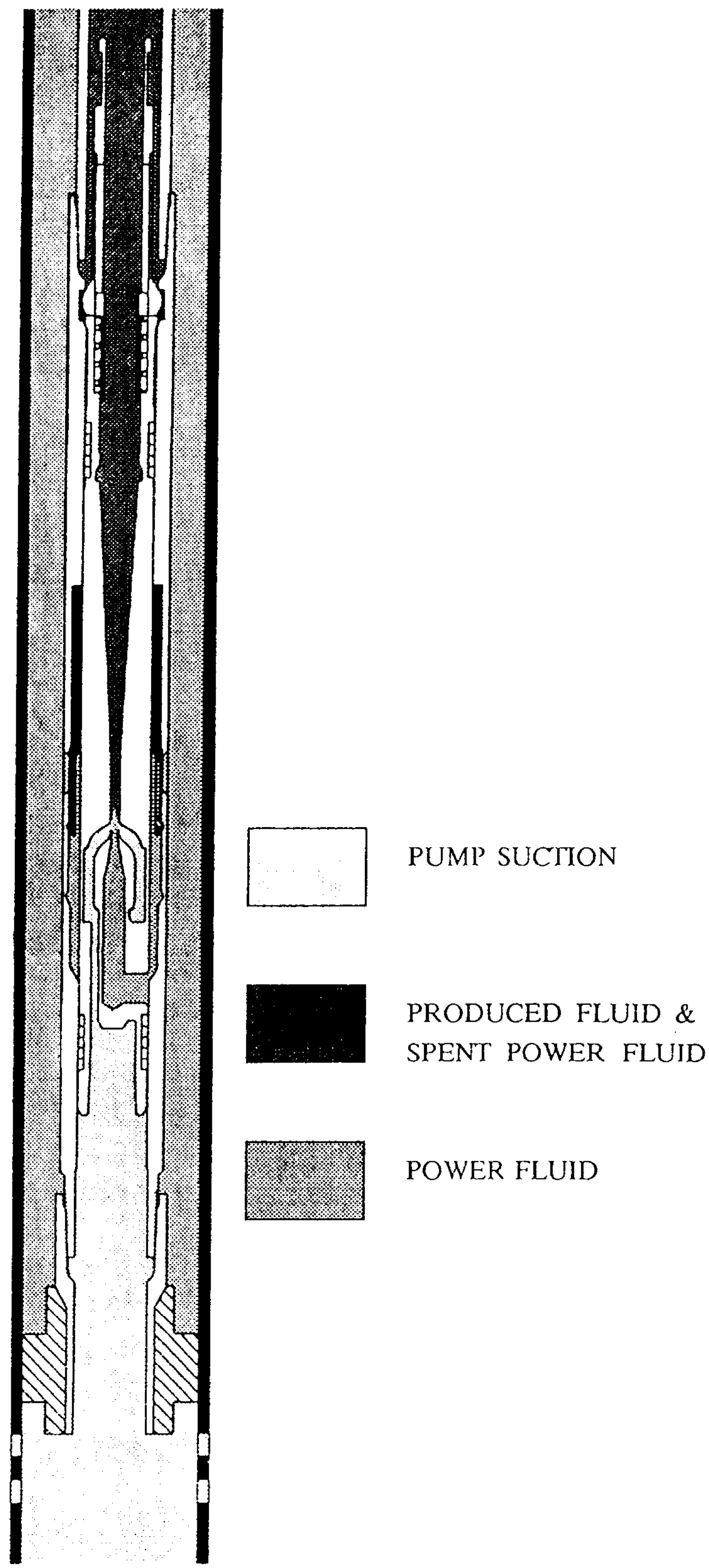

Figure 3 - Sliding sleeve jet pump with top lock and seal mandrels, reverse flow arrangement
Typical of drill stem test unit

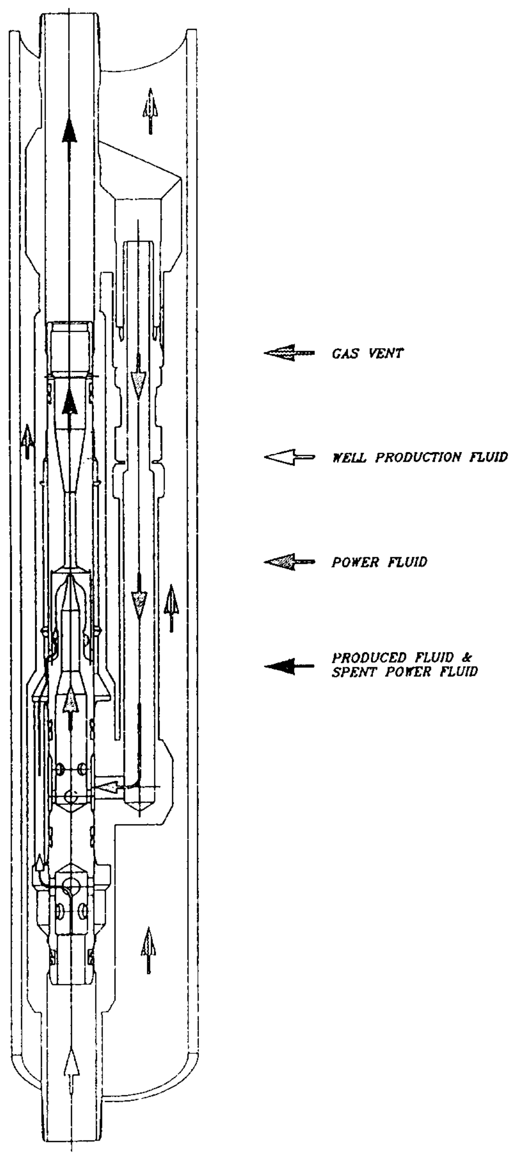

Figure 4 - High volume jet pump reverse flow in a "parallel free" bottom hole assembly

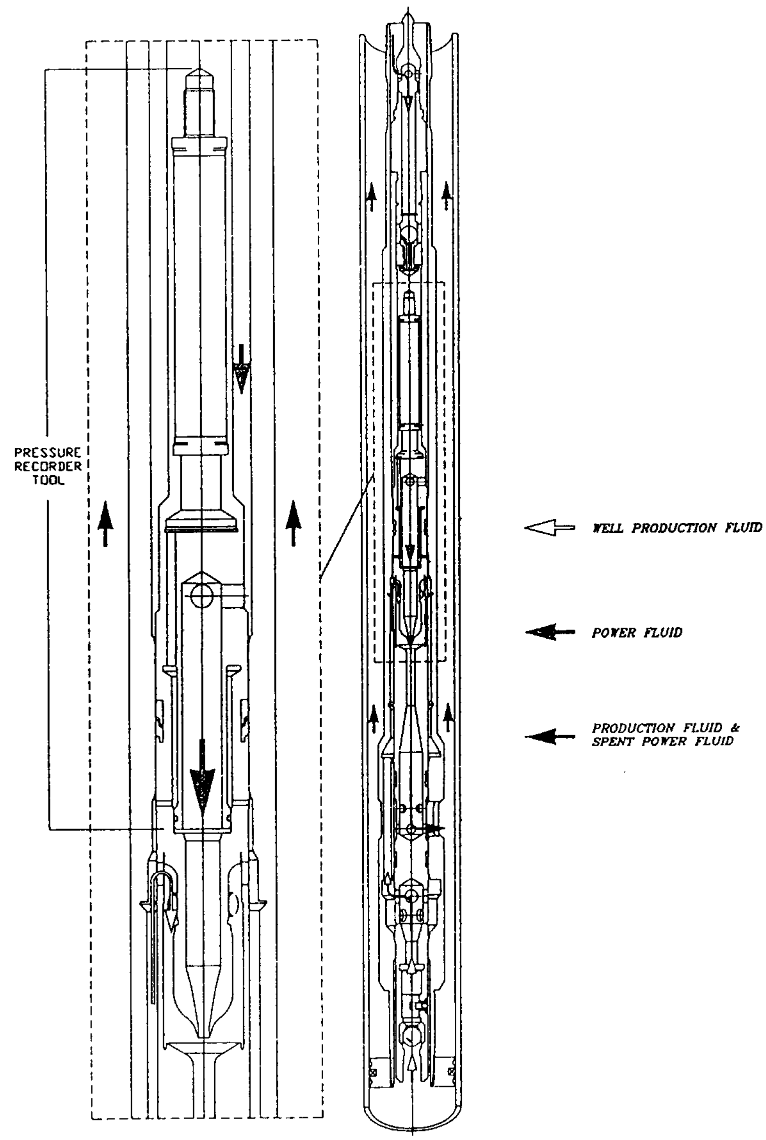

Figure 5 - High volume jet pump with top mounted pressure recorder tool which can produce a "current" PI curve for the well

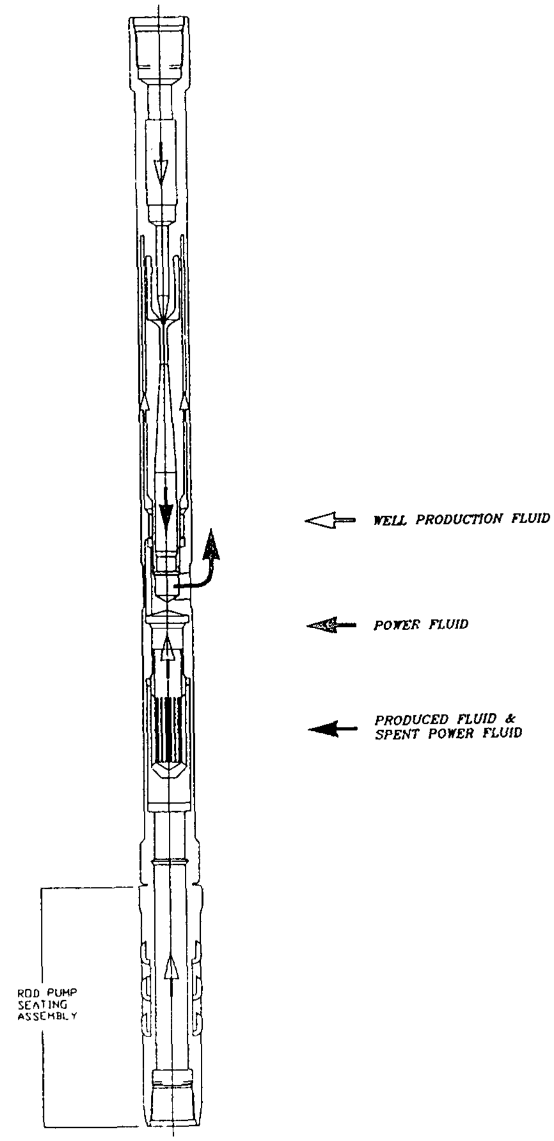

Figure 6 - Small diameter jet pump for concentric, inside the tubing production

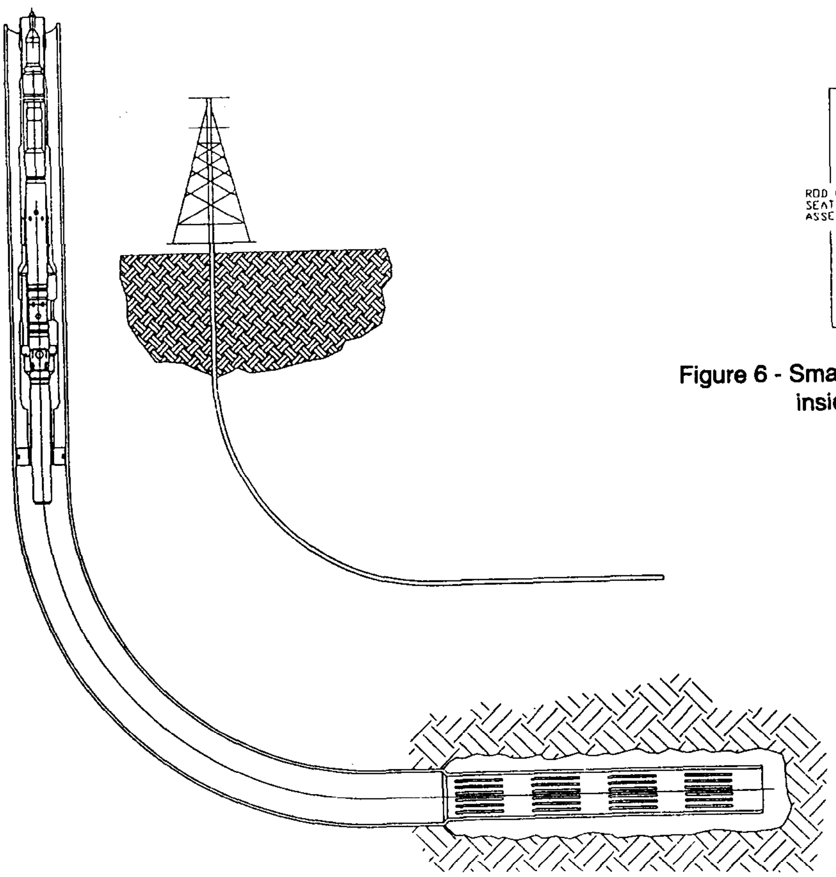

Figure 7 - A common "current" horizontal well completion with a slotted liner. Due to packer placement, jet pump set in vertical section