IRON COMPOUNDS AND ASSOCIATED SCALE CONTROL IN OIL AND GAS WELLS USING MAGNETIC BAILER

Sarfraz A. Jokhio
Wood Group ESP, Inc.

ABSTRACT

A magnetic bailer has been designed to capture and remove metallic compounds that gather in the wellbore and downhole operating equipment such as an ESP unit. The tool can be used as a standalone, as the part of the tubing, or can be set in the tubing as a joint that stands on Y-tool. The tool can be installed above or below the ESP unit. It can be wireline or coil tubing operated. It is, a cost effective and convenient physical way of cleaning the well. It can save significant well shut-in times that are otherwise unavoidable due to pump failure.

Many producing formations produce metal compounds along with oil, gas and water. These metal compounds often are iron-associated compounds, heavy and usually settle in the wellbore. Often iron compounds combine with hydrogen sulfide (H_2S) and sulfur dioxide **(SO,),** usually present in natural gas, to form iron sulfide in the wellbore. Iron sulfide is a very hard material (*SG* 5.1 +). It is not malleable and has crystalline and abrasive structures. When iron sulfide enters an ESP unit, it damages the impellers, diffusers, and shaft, thereby reducing the pump run time and causing premature pump failure. Most of the time, it juggles in the fluid that is being pumped and falls back when the pump stops. It is not carried to the surface due to its high specific gravity, it instead sticks to the tubing walls above the pump, and most of the time in the first tubing joint, and with time completely plugs the tubing. Chemical treatment is usually not effective since the inhibitor is pumped out of the well.

In this paper the physical properties of iron compounds in general and iron sulfide in particular, along with common contaminant compounds found in crude oil and natural gas and problems associated with iron compounds and associated scale are investigated. Second, the first indications of their presence and the unusual solids in the pump are addressed, and finally the tool design is discussed in detail.

INTRODUCTION

Many oil-producing areas in the world contain iron compounds in the formations that flow with the oil, gas, and water in the form of fines. One such area is the Indian Basin, New Mexico. The downhole environment in Indian Basin is very severe. Wellbore temperature ranges between 160-220°F, and produced gas contains a significant amount of H_2S. The main production in the Indian Basin is natural gas, but wells produce on average 1,000-2,000 STB/D of water and have to be unloaded using ESPs. The water quality is very poor. It contains significant amount of carbonate, bicarbonate, sulphate, magnesium, and sodium ions. Table 1 shows the water analysis from a well in the Indian Basin.

The metal fines react with H_2S and other sulfur containing gases and compounds that are present in the crude oil and natural gas to form iron sulfide and other iron containing compounds. The wellbore temperature environment seems to favor such conditions. These compounds are heavy, hard, and crystalline in nature, Fig.3, Fig.4-a, and Fig.4-b. When combined with high velocity gas they create a sand blast like effect, destroying the downhole infrastructure and premature pump failure. Recently, Indian Basin has been the hard hit with such scale, which is mainly iron sulfide (FeS_2) in nature. The iron outcrops in Indian Basin even can be seen at the surface, indicating the presence of the iron ore in the area. Most of the wells are high profile gas wells producing 5-7 MMscf/D. The liquid is pumped through tubing using ESP units set below the perforations to get effective liquid-gas separation and gas is produced through the casing. The scale impact on the downhole infrastructure is on both sides of the tubing. Water related scale and iron sulfide scale inside the tubing and H_2S related scale behind the tubing could be seen. Chemical treatment is being tried at the present but it is a temporary solution of the problem since most of the inhibitor is pumped out.

After cleaning with acid, pumps show severe efficiency loss. Most of the impellers wear out soon and shaft life is shortened. Several teardown reports show the collection of metal solids in the pump impellers and diffusers. Table 2 shows the percent iron compounds content in scale samples along with calcium carbonate scale collected from seven different wells. Calcium carbonate related scale precipitates from the hard water when it comes in contact with hot motor surface. It often collects on the motor housing thereby reducing the cooling of the motor and flow area between the motor and the shroud. Most of the units in Indian Basin are shrouded units. The scale deposition is slow and progressive. Calcium scale looks like a cement sheath on the motor housing, as indicated by Fig.24, and in many cases the shroud had to be cut to release the pump. In this article, however, the ways to control iron-associated scale has been investigated, as it is the highest fraction of the scale analysis as indicated by Table 2.

Frequent pump failure, along with the service cost and workover cost, is the main reason of the well shutdown and revenue loss.

CONTAMINANT COMPOUNDS COMMONLY FOUND IN PETROLEUM FLUIDS

The main contaminants in natural gas are:

1. Hydrogen sulfide (H_2S)
2. Nitrogen (N_2)
3. Carbon dioxide (CO_2)
4. Sulfur
5. Water vapors

H_2S is the main source of the corrosion in the oil and gas wells and it also reacts with most iron compounds and the problem is further aggravated by the presence of water vapors.

IRON COMPOUNDS

Iron forms compounds such as oxides, hydroxides, halides, acetates, carbonates, sulfides, nitrates, sulfates, and a number of complex ions. It **is** chemically active and forms two major series of chemical compounds, the bivalent iron (II), or ferrous, compounds and the trivalent iron (III), or ferric, compounds. Ferrous sulfate heptahydrate, $FeSO_4 \cdot 7H_2O$, sometimes called green vitriol, is a compound formed by the reaction of dilute sulfuric acid (formerly called oil of vitriol) with metallic iron; it is used in the manufacture of ink, in dyeing, and as a disinfectant. Ferric chloride hexahydrate, $FeCl_3 \cdot 6H_2O$, is a yellow-brown crystalline compound used as a mordant in dyeing and as an etching compound. Ferric oxide, Fe_2O_3, is a reddish-brown powder used as a paint pigment and in abrasive rouges. Prussian blue, $KFe_2(CN)_6$, is a pigment containing the ferrocyanide complex ion. Iron rusts readily in moist air, forming a complex mixture of compounds that is mostly a ferrous-ferric oxide with the composition Fe_3O_4.

PHYSICAL PROPERTIES OF IRON SULFIDE

Chemistry: FeS_2
Color: Brassy yellow,
SG: 5.1+ (> average Metals)
Luster: Metallic
Crystal Habits:
- Include the cube,
- Octahedron and
- Pyritohedron

Hardness: 6 - 6.5 (Gold: 2.5 – 3, and Diamond: 10, Tungsten Carbide: 9.5)
Other Characteristics:
- Brittle,

Associated Minerals
Quartz,
Calcite,
Gold

PHYSICAL PROPERTIES OF IRON SULFATE

Iron sulfate, $FeSO_4$ when combined with water, is known as monohydrate, $FeSO_4 \cdot H_2O$; tetrahydrate, $FeSO_4 \cdot 4H_2O$; the pentahydrate, $FeSO_4 \cdot 5H_2O$; and heptahydrate, $FeSO_4 \cdot 7H_2O$. The heptahydrate is also called green vitriol, copperas, or melanterite (a mineral that commonly occurs with pyrite.). It is a blue-green monoclinic crystalline water-soluble salt. It is prepared commercially by oxidation of pyrite (iron sulfide) or by treating iron with sulfuric acid. It is used in the manufacture of inks, in wool dyeing as a mordant, and in water purification as a substitute for aluminum sulfate. It melts at 64°C;, and at 90°C; it loses water of hydration to form the monohydrate, a white, monoclinic, crystalline powder that occurs naturally as the mineral szomolnokite. The mineral siderotil is iron sulfate pentahydrate'

PROBLEMS ASSOCIATED WITH IRON COMPOUNDS

Iron compounds are heavy. Iron sulfide is heavier than average metals. It is not malleable and has a specific gravity of 5.1+, greater than average metals. ESP pump impellers are made of NiChrome metals that are softer than the iron sulfide, thus it physically damages the pump as indicated by Fig.18 through Fig.20. Since it is heavy, it does not pump out of the well and falls back and collects around the first few joints above the pump as shown in Fig.5. Slowly and progressively it chokes the tubing and locks the pump. The first signs of its presence are indicated by the surface amp chart, which shows the presence of the particles in the pump (Fig.1).

WHAT SHOULD WE DO ABOUT IT?

The quantity of the scale is so overwhelming that continuous injection of inhibitor is needed. This is not always possible for Indian Basin wells since they produce from the annulus about 5-7 MMscf/D. It is feared that the liquid inhibitor may get mystified and flown back with the gas. If the inhibitor reaches the wellbore it will be pumped out of the well through tubing. It is a temporary solution of the problem. We looked from a physical control point of view, for a means to control the iron compounds, usually iron sulfide, using a tool installed either below the pump or using a Y-tool so that particles do not even enter the pump. The tool can be cleaned periodically without rig if the Y-tool option is chosen. Fig.12 shows such configuration showing the magnetic bailer set in the tubing with a Y-tool. The tool is a wireline operated and can be pulled out using a cable spooler truck. Once the tool is taken out, it can be sent to maintenance shop for cleaning, second tool can be set at the time first tool is pulled, thus saving significant well shut-in time.

Tool length can be designed to accommodate a sufficient amount of the solid accumulation providing significant run time. Reduction in surface liquid rate is a good indication of the tool being saturated with solids.

MATHEMATICAL BASIS

Assuming a solid particle of mean diameter, d_s, and specific gravity, SG, is in suspension in the liquid flowing at the rate q_L and is flowing with liquid of viscosity m_L, and specific gravity SG,, at a velocity V_s. The forces acting on the particle in the presence of the magnetic field are as follows, Fig.6:

1. Buoyancy Force: Buoyancy force acting on the particle acts upward and trying to keep the particle in suspen sion. This force, F, is equal to the

$$F_{bo} = (P_i - P_{hs}) * A$$

Where P_i is the pressure at location of the particle in the bailer. This is roughly equal to the wellbore flowing pressure. P_{hs} is the hydrostatic pressure at that point. A is the area of the particle. In case of a sphere the total surface area is $4pr^2$. For example at 10,000 ft, if ESP is pumping water as main fluid of SG 1.1, the buoyancy force on the particle of 5.1 SG and 0.01 in diameter, assuming half of the particle is exposed, is

$$A = 2\pi r^2$$

$$A = 2\pi(0.01/2)^2 = 0.00015708 \text{ sq. inch}$$

$P_{hs} = (0.433)(1.1)(10,000) = 4,763$ psi

P_i = Pwf = 5,000 psi

$F'_{bo} = (5,000-4763)(0.00015708) = 0.037228$ Ibf

The effective weight, W_e, of the particle in fluid then is:

$$W_e = W[1-(\rho_f/\rho_S)]$$

Where W is the weight in air of the solid, ρ_f is the density of the fluid, and ρ_S is the density of the solid. The weight force of the particle then is

$$F_g = W_e$$

The effective SG of the particle in the fluid is

SG = 5.1 (1-(1.1/5.1) = 4

Mass **of** the sphere of iron sulfide

M = density * Volume

$$V = \frac{4}{3}\pi r^3$$

$$V = \frac{4}{3}\pi(\frac{0.01}{2*12})^3 = 3.03 \times 10^{-10} \text{ cu ft}$$

Density of solid particle in air = 5.1 (62.4) (1.1) = 350.064 lb/cuft
Mass = (3.03 x 10^{-10}) (350.064) = 1.0607 x 10^{-7} lbs
Acceleration due to gravity = 32.174 ft/ sec^2
Weight of solid in air = 32.174 (1.0607 x 10^{-7})
Weight of solid in air = 3.41x 10^{-6} lb
Weight in liquid, W_e = (3.41x 10^{-6})[1-{350.064/(62.4*1.1)}] = 2.74 x 10^{-6} lbf

2. Velocity Force, F : The velocity force acting on the particle is equal to the mass times the velocity of the particle. The velocity of the particle is equal to the velocity of the fluid minus the slip velocity of the particle.

Assuming 2,000 B/D passing through a perforated plate of 0.5 inch single hole the velocity of the fluid is

$$A = \pi r^2$$

$$A = \pi(\frac{0.5}{2*12})^2 = 0.00136 \text{ sq. ft}$$

q_L = 2,000 * 5.6145/(24*60*60) = 0.1299 cu ft/ Sec

Velocity = 0.1299 10.00136 = 95.5 ft / sec

This is the velocity if all the fluid (2,000 B/D) passes through single 0.5 in hole. If the plate has **8** holes then velocity through each hole is

Velocity = 95.5/8 = 11.9375 ft/sec.

3. The effective velocity of the solid particle is the difference of fluid velocity and the slip velocity.

Slip velocity is calculated as follows';

Assuming Stokes law applies

$$V_{sl} = \frac{138(\rho_s - \rho_f)d_s^2}{\mu_f}$$

The density in above equation density is ppg.

$$V_{sl} = \frac{138[5.1(8.33) - (8.33)1.1](0.01^2)}{1} = 0.46 \text{ ft/Sec}$$

This is assumed velocity. Now calculate the slip velocity that corresponds to the friction factor and Reynolds number.

$$f = \frac{3.57(\rho_s - \rho_f)d_s}{\rho_f V_{sl}^2}$$

$$f = \frac{3.57[5.1(8.33) - 1.1(8.33)](0.01)}{(8.33*1.1)(0.46)^2} = 0.61$$

Calculate the Reynolds number for particles

$$R_e = \frac{928\rho_f Vsld_s}{\mu_f}$$

$$Re = \frac{928(8.33*1.1)(0.46)(0.01)}{1} = 39.11$$

Now locate the point R_e = 39.11 and f = 0.61 on Fig.21 and move along the slanted lines to a value of proper spherecity (ψ).

W assumed 0.85, and determined the new values of R_e and f as;

R_e = 20 and f = 4.

Now recalculate the slip velocity using following equation.

$$V_{sl} = 1.89\sqrt{\frac{(\rho_s - \rho_f)}{\rho_f}\left(\frac{d_s}{f}\right)}$$

$$V_{sl} = 1.89\sqrt{\frac{(5.1-1.1)8.33}{(8.33*1.1)}\left(\frac{0.01}{4}\right)} = 0.18 \text{ ft/sec}$$

The effective velocity of the particle is 95.50-0.18 = 95.32 ft/sec

The velocity force = (95.32)(2.74 x 10^{-6}) = 2.6117 x 10^{-4} lbf

4. Pressure force, F_p : Pressure force acting on the particle is equal to the pressure times the area of the particle.

F_p = 5,000 (0.00015708) = 0.7854 lb_f

Thus the total force acting on the particle is

$F_t = F_b + F_v + F_p - F_w$

F_t = 0.037228 + 2.6117 x 10^{-4} + 0.7854 − 2.74 x 10^{-6}

F_t = 0.823 lb_f

Thus magnetic force needed to trap the solid particle should be greater than the total force.

The tool is under construction at the time this article is being written. It will be tested for pressure and particle retention in the month of April, 2002. Once tested it will be installed in Indian Basin along with other scale control measures.

COMMERCIALLY AVAILABLE MAGNETS

Modem permanent magnets are made of special alloys that have been found through research to create increasingly better magnets. The most common families of magnet materials today are ones made out of Aluminum-Nickel-Cobalt (Alnicos), Strontium-iron (Ferrites, also known as Ceramics), Neodymium-iron-Boron (Neo magnets, sometimes referred to as “Super magnets”), and Samarium-Cobalt. (The Samarium-Cobalt and Neodymium-iron-Boron families are collectively known as the Rare Earths.)

Modem magnet materials do loose a very small fraction of their magnetism over time. For Samarium Cobalt materials, for example, this has been shown to be less than 1% over a period of ten years.

Factors that can affect a magnet’s strength are:

- Heat
- Radiation
- Strong electrical currents in close proximity to the magnet
- Other magnets in close proximity to the magnet
- (Neo magnets will corrode in high humidity environments unless they have a protective coating.)

Shock and vibration do not affect modern magnet materials, unless sufficient to physically damage the material.

The strength of a magnetic field drops off roughly exponentially over distance. Here is an example of how the field (measured in Gauss) drops off with distance for a Samarium Cobalt Grade I8 disc magnet which is 1" in diameter and 1/2“ long.

For a circular magnet with a radius of R and length L, the field at the centerline of the magnet a distance X from the surface can be calculated by the following formula:

$$Field = \frac{B_r}{2}\left[\left(\frac{L+X}{R^2+(L+X)^2}\right) - \frac{X}{(R^2+X^2)^{1/2}}\right]$$

Where B_r is the Residual Induction of the material.
Provided that the material has not been damaged by extreme heat, the magnet can be re-magnetized to its original strength. Once a magnet is fully magnetized, it cannot be made any stronger - it is "saturated". In that sense, magnets are like buckets of water: once they are full, they can't get any "fuller".

Most commonly, Gaussmeters, Magnetometers, or Pull-Testers are used to measure the strength of a magnet. Gaussmeters measure the strength in Gauss, Magnetometers measure in Gauss or arbitrary units (so it is easy to compare one magnet to another), and Pull-Testers can measure pull in pounds, kilograms, or other force units.

There are two types of magnets: permanent magnets and electro-magnets.
Permanent magnets emit a magnetic field without the need for any external source of power. Electro-magnets require electricity in order to behave as a magnet.

There are various different types of permanent magnet materials, each with their own unique characteristics. Each different material has a family of grades that have properties slightly different from each other, though based on the same composition.

Most modem magnet materials have a "grain" in that they can be magnetized for maximum effect only through one direction. This is the "orientation direction", also known as the "easy axis", or "axis".
Unoriented magnets (also known as "Isotropic magnets") are much weaker than oriented magnets, and can be magnetized in any direction. Oriented magnets (also known as "anisotropic magnets") are not the same in every direction -they have a preferred direction in which they should be magnetized.

POTENTIAL BENEFITS

Potential benefits of physical solid control include:

1. The solids are intended to trap before they enter the pump thereby increasing pump life, run time, and avoid premature failure.
2. Chemical treatment is temporary, since inhibitor is pumped out of the well. The increase in tool length allows operating the tool for longer times.
3. The tool is reusable.
4. It can be operated without a rig, thereby, saving rig and service cost.

CONCERNS

The major concern regarding the tool is that the tool may get saturated with trapped solids and completely choke the tubing. Thus a plate with larger holes is preferred. Also only one hole magnetic plate can be used, thus enough space around the hole is left so that the iron sulfide can build as on its edge. This settling behavior of the iron sulfide has been seen in the field. Since, the tool is in production, it is believed that much will be learned during its testing phase. Another concern is that the magnetic material can erode with the fluid flow through it. Thus, stronger magnetic material is preferred. Also the viscous liquids may actually build the adhesive mixture of the solids and the oil can choke the plate. In such situations frequent cleaning of the tool may required.

CONCLUSIONS

1. In this article we have approached the iron compounds and related scale control in oil and gas wells using physical measures such as magnets to separate the solids from the fluid stream and remove from the well before they enter the costly **ESP** equipment.
2. The tool can be used either wireline operated or standalone as a part of the tubing.
3. In its design, principles of physics have been used to capture the particles.
4. It is reusable.
5. If wireline or coil tubing operated, it can save significant well shut in times.

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3. Bourgoyne Jr..A.T et al. Applied Drilling Engineering, SPE Text Book Series, Vol.2.
1. Centrilift, Submersible Pump Handbook, Sixth Edition.
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Table 1
Water Analysis from a Well in Indian Basin Showing the PPM Concentration of the Various Ions
Courtesy: Champion Technologies Inc.

Date	Cl	SO_4	HCO_3	Ca	Mg	Fe
6/8/2001	244,000	5,150	122	1,604	583	2
	pH	CO_2	H2S	Na		
	6.2	310	2	15,780		

Table 2
Scale Analysis of Seven Different Wells in Indian Basin, NM. The well identity has been changed.
Courtesy: Champion Technology Inc.

Well	Date	H_2O Sol.	HC	$CaCO_3$	Fe++	Acid Insolubles
		%	%	%	%	%
X-1	7/1/01	0.9	3.6	14.1	62.3	19.1
X-2	7/12/ 1	1.4	8.5	7	76.1	4.2
X-3	7/ 2/ 1	8.5	1.3	17.	57.5	15.7
X-3	7/12/ 1	0.0	7.3	8.7	72.3	11.7
X-4	5/ 4/ 1	6.9	7.9	11.4	59.9	13.9
X-4	6/ 7/ 1	0.4	10.8	17.7	56.3	14.8
X-4	6/13/ 1	9.7	17.3	26.	12.2	0.5
X-5	7/16/ 1	1.8	2.2	72.9	18.2	1.4
X-6	8/14/ 1	0.0	2.7	7.7	78.2	11.4
X-7	6/ 7/ 1	12.	2.3	26.3	41	18.4

Table 3
The Magnetic Field as a Function of Distance

Distance, X	Field at Distance X	Distance, X	Field at Distance X
0.063	2,690	0.563	680
0.125	2,320	0.625	580
0.188	1,970	0.688	490
0.250	1,660	0.750	420
0.313	1,390	0.813	360
0.375	1,160	0.875	310
0.438	970	0.938	270
0.500	810	1.000	240

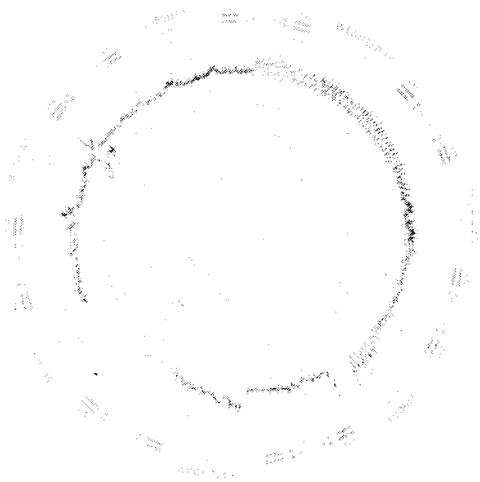

Figure 1 - The Amp Chart of a Well in Indian Basin Indicating Presence of Gas and Solids in the Pump. The well is a gas well so presence of gas is not unusual.

Figure 2 - Iron Sulfide Scale Sample Taken from the First Joint Above the Pump

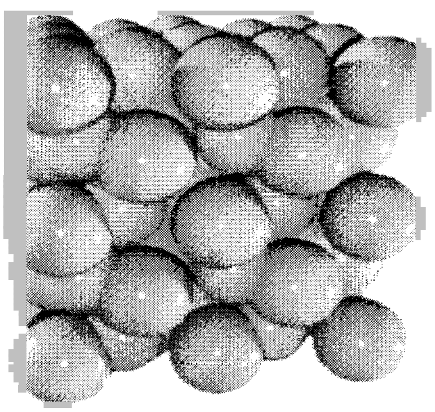

Figure 3 - Molecular Structure of Iron Sulfide

Figure 3 - Magnetic Nature of Iron Sulfide Sample

Figure 4a - Crystal Nature of the Iron Sulfide

Figure 4b -. Crystal Nature of the Iron Sulfide

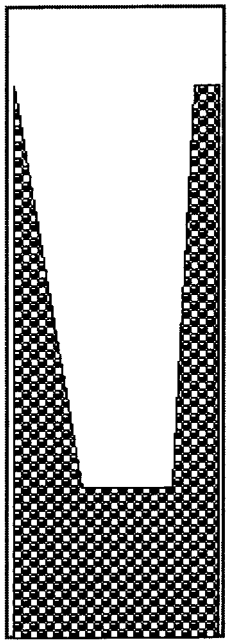

Figure 5 - Mode of Iron Sulfide Settling in the Tubing as Observed and Reported by the Field Workers

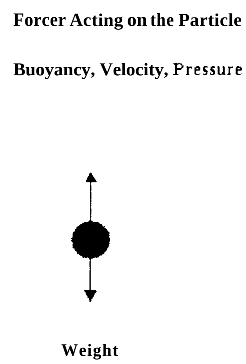

Figure 6 - Forces Acting on the Particle in the Fluid

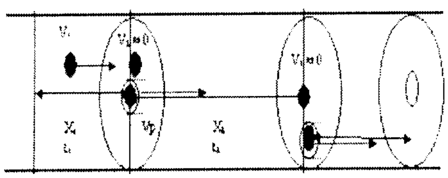

Figure 7 - Particle Trapping Mechanism in the Magnetic Bailer

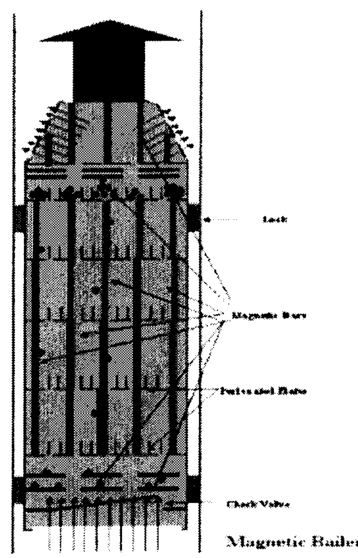

Figure 8 - Bailer Design

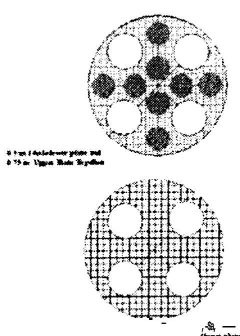

Figure 9 - Eight-Four Hole Plate Configuration for the Bailer

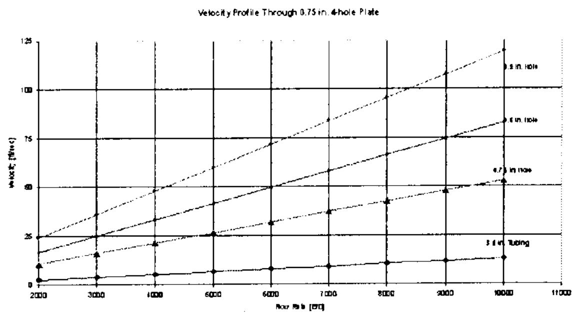

Figure 10 - Velocity Profile of Particle in 0.5 in. Diameter 4-Hole Plate

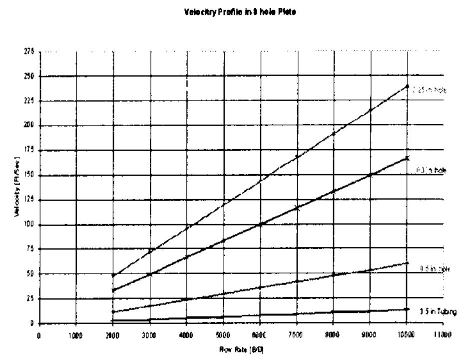

Figure 11 - Velocity Profile of Particle in 0.75 in. Diameter 4-Hole Plate

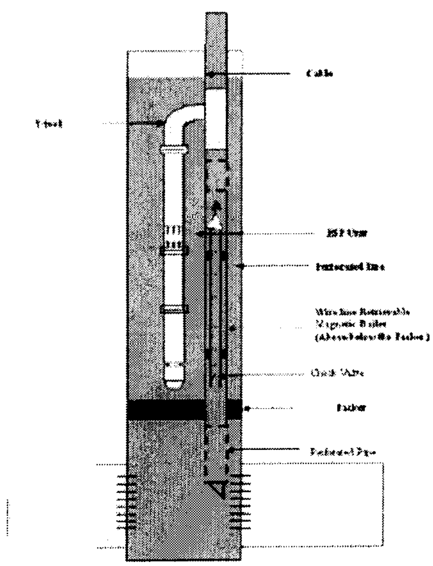

Figure 12 - Bailer in the Well Set with Y-tool

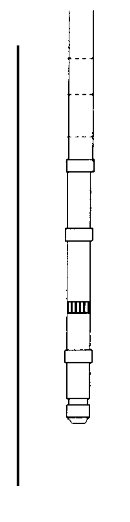

Figure 13 - Bailer Set Above the Pump as a Part of the Tubing

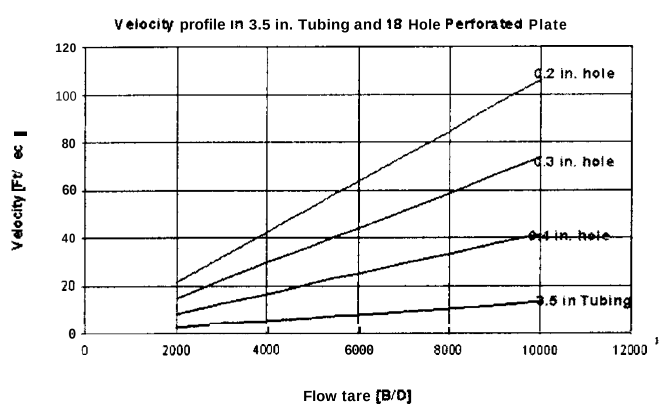

Figure 14 - Velocity Profile of Particle in the 18-Hole Plate and 3.5 in. Tubing

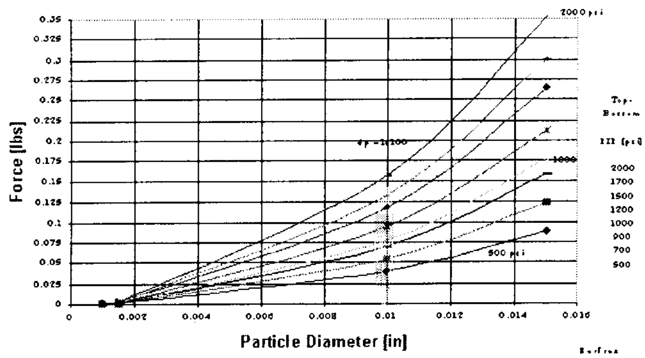

Figure 15 - Pressue Forces on the Particle

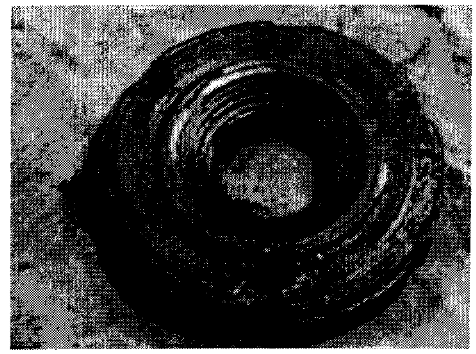

Figure 16 - Damaged Impeller Due to Solids

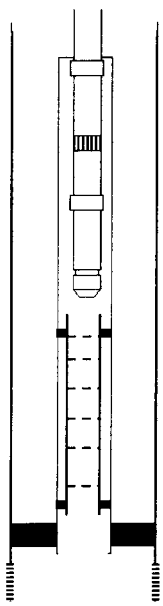

Figure 17 - Bailer Set Below the Pump as a Part of the Tubing

Figure 18 - Solid accumulation on the impeller

Figure 19 - Settled Solids in the Diffuser

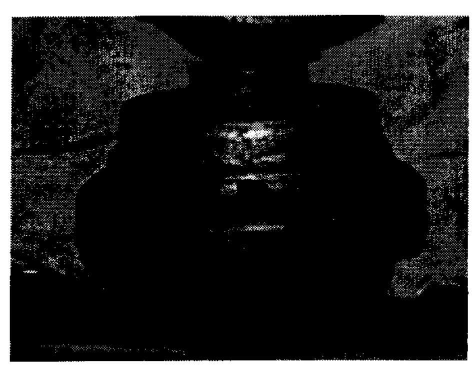

Figure 20 - Eroded Impeller Due to Presence of Solids

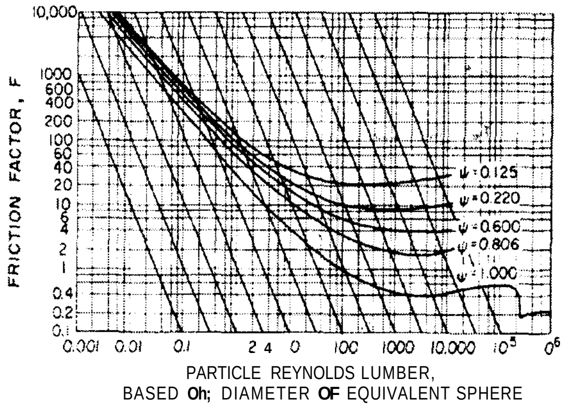

Figure 21 - Particle Reynolds Number and Friction Factor[3]

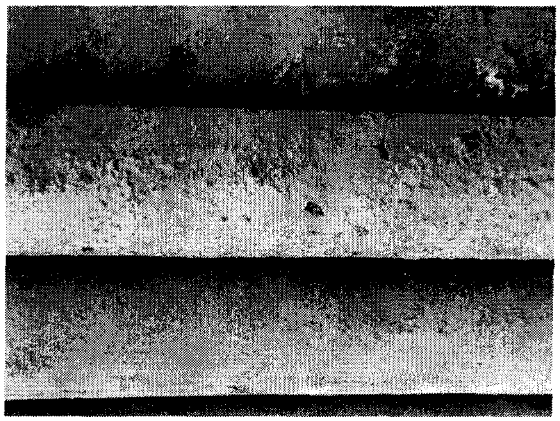

Figure 22 - Iron Sulfide Scale Behind the Tubing

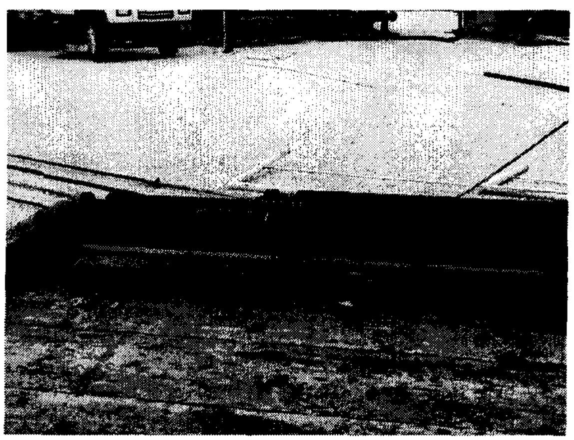

Figure 23 - Iron Sulfide Scale Outside the Pump

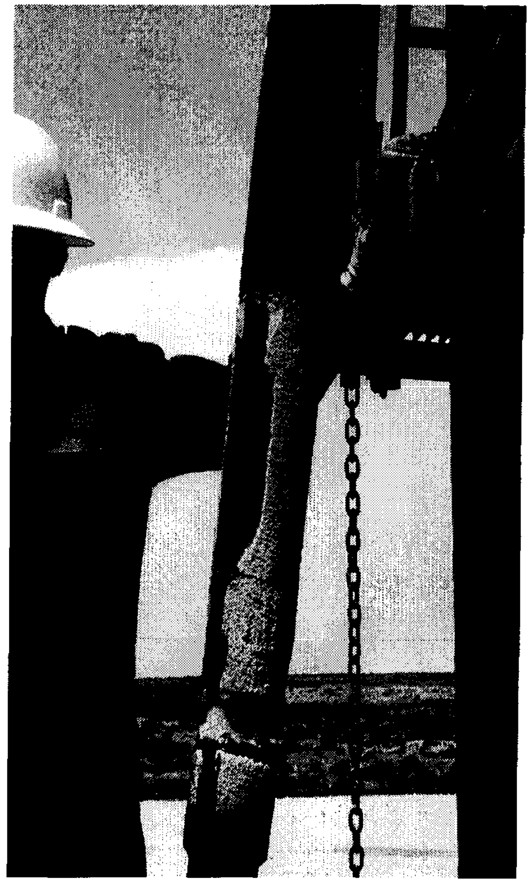

Figure 24- Calcium Carbonate Scale Deposition on the Motor Housing