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Subsurface pressure regulation of high pressure condensate wells

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SUBSURFACE PRESSURE REGULATION OF HIGH PRESSURE CONDENSATE WELLS

BY

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A

THESIS

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ABSTRACT

The discovery of deeper production and higher pressures has resulted in the need for control equipment for preserving and protecting these great reservoirs of energy; and, in the case of high pressure condensate wells, has resulted in the need for means for preventing freezing or hydrate solidification caused by throttling the production. Development of a successful removable subsurface regulator has enabled operators to reduce dangerously high surface flowing pressures to safe workable limits; and, by moving the point of principal pressure reduction from the surface to warmer subsurface levels, has resulted in complete elimination of freezing conditions in flow lines. Development and operation of the regulator are described, and charts and tables for use in determining proper depths and pressure reductions for preventing freezing are shown. Other results, heretofore considered subordinate, such as reduction and stabilization of condensate ratios, and retarding of water encroachment, have been observed. Possibility of the use of subsurface regulators to establish conditions in the tubing string most favorable

for condensate precipitation is noted. Further technical research is desired relative to the use of subsurface regulators for controlling temperatures and pressures in the flow string to obtain conditions most conducive to condensate precipitation and an increased condensate recovery.

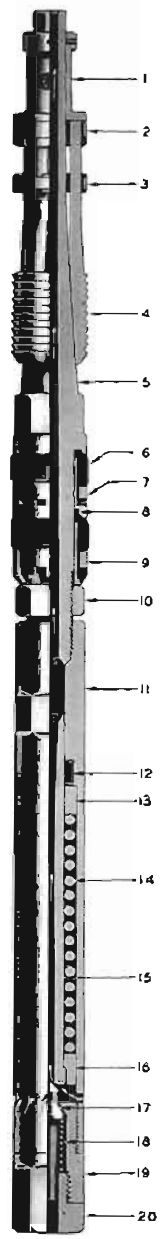


FIG. 1

Type B
Otis Removable
Bottom Hole
Regulator

1. *Slip Carrier*
2. *Slip Carrier Band*
3. *Mandrel Band*
4. *Slips*
5. *Mandrel*
6. *Otis Sealing Cup*
7. *Upper Sealing Cup Ring*
8. *Cup Ring Packing*
9. *Lower Sealing Cup Ring*
10. *Cup Nut*
11. *Valve Cage*
12. *Chevron Packing*
13. *Adjusting Ring*
14. *Regulating Spring*
15. *Valve Seat*
16. *Valve Seat Guide*
17. *Valve*
18. *Valve Spring*
19. *Valve Housing*
20. *Valve Housing Plug*

TABLE 2

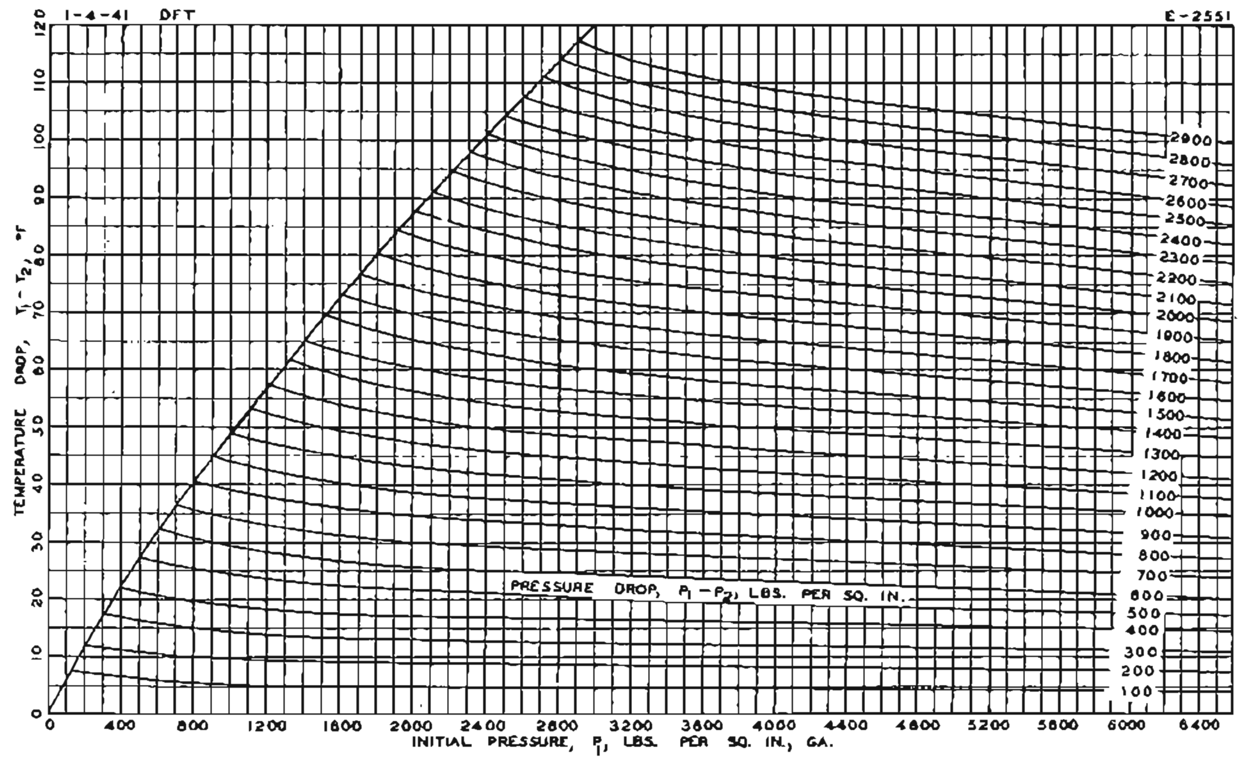
Subsurface temperature of oil fields in Texas and Louisiana

Division and Field	Producing Formation	Sub-Sea Depth	Temp. °F.	*Geothermal Gradient Feet per 1° F. Increase	Type of Structure
East Texas					
East Texas	Woodbine	3300	146	50.00	Stratigraphic Trap
Navarro Crossing	Woodbine	5546	184	53.31	Piercement Type Salt Dome
Oakwood	Woodbine	5610	186	52.92	Anticline Faulted
Van	Woodbine	2425	136	43.30	Deep Seated Dome Faulted
Talco	Paluxy	3785	147	56.49	Anticline Faulted
Willow Springs	Glenn Rose	6925	221	49.11	Anticline Faulted
Gulf Coast					
Amelia	Frio	6480	164	77.14	Deep Seated Dome Faulted
Anahuac	Frio	7050	178	71.93	Deep Seated Dome Faulted
Cedar Point	Frio	5585	172	60.70	Deep Seated Dome Faulted
Danbury	Frio	5500	178	56.12	Piercement Type Salt Dome
Dickinson (8000')	Frio	8000	199	67.22	Deep Seated Dome Faulted
(9100')	Frio	9050	217	66.13	Part of Dickinson Structure:
(Gillock)	Frio	8750	207	68.89	Faulted Blocks
Friendswood	Frio	5800	164	69.04	Deep Seated Dome Faulted
Hastings	Frio	6000	170	66.66	Deep Seated Dome Faulted
Lovell Lake	Frio	7475	172	81.25	Deep Seated Dome Faulted
Pledger	Frio	6730	170	74.77	Deep Seated Dome Faulted
Roanoke	Frio	8390	196	72.32	Deep Seated Dome Faulted
Sugarland	Frio	3600	156	47.36	Semi-Deep Seated Piercement Type Dome
Thompsons	Frio	5250	162	64.02	Deep Seated Dome Faulted
Withers (Magnet)	Frio	5350	152	74.30	Elongated Deep Seated Faulted Dome
N. Crowley	Frio	8600	196	74.13	Deep Seated Dome Faulted
Vanderbilt	Frio	5530	166	64.30	Deep Seated Dome Faulted
Conroe	Cockfield	4900	172	53.26	Deep Seated Dome Faulted
Hardin	Cockfield	7610	196	65.60	Faulted Regional Uplift
Livingston	Cockfield	4115	158	52.75	Deep Seated Dome Faulted
Raccoon Bend	Cockfield	3850	156	50.65	Deep Seated Dome Faulted
Segno	Cockfield	5060	165	59.52	Deep Seated Dome Faulted
Tomball	Cockfield	5380	182	52.74	Deep Seated Dome Faulted
N. Cotton Lake	Marginulina	6145	156	80.85	Closure on Fault (Part of South Cotton Lake Structure)
S. Cotton Lake	Marginulina	6320	156	83.16	Elongated Faulted Regional Anticline
Hastings	Marginulina	5700	162	69.51	Deep Seated Dome Faulted
Roanoke	Marginulina	8630	201	71.32	Deep Seated Dome Faulted
N. Crowley	Marginulina	7970	188	73.79	Deep Seated Dome Faulted
N. Crowley	Miocene	7020	169	78.87	Deep Seated Dome Faulted
Thompsons	Miocene	3450	146	52.27	Deep Seated Dome Faulted
West Columbia	Miocene	2810	126	61.08	Piercement Type Salt Dome
Goose Creek	Miocene	2580	115	73.71	Deep Seated Dome Faulted
Cameron Meadows	Miocene	3925	139	66.52	Piercement Type Salt Dome
Barbers Hill	Miocene	4500	136	80.35	Piercement Type Salt Dome
Darrow, La.	Fleming	5760	167	66.20	Piercement Type Salt Dome
Hull	Saline Bayou	4500	145	69.23	Piercement Type Dome
Katy	Saline Bayou	7000	170	77.77	Deep Seated Dome
Kittrell	Carrizo	1710	121	41.70	Piercement Type Salt Dome
Lake Hermitage	Miocene	3175	117	85.81	Piercement Type Salt Dome
Lake Washington	Cap Rock	1125	104	46.87	Piercement Type Salt Dome
N. Crowley	Discorbis	7945	186	74.95	Deep Seated Dome Faulted
Raccoon Bend	McElroy	3250	142	52.41	Deep Seated Dome Faulted
Roanoke	Heterostegina	7790	187	72.80	Deep Seated Dome Faulted
Segno	Wilcox	7540	221	53.47	Deep Seated Dome Faulted
S. Liberty	Saline Bayou	4925	142	79.43	Piercement Type Salt Dome
Southwest Texas					
Flour Bluff	Frio	6650	185	63.33	Deep Seated Dome Faulted
Greta	Frio	5750	177	59.27	Anticline Faulted
Heyser	Frio	5360	164	63.81	Sand Lenses on Anticline
Kelsey	Frio	4495	158	57.62	Anticline
Kelsey	Frio	5800	182	56.86	Anticline
Plymouth	Frio	5575	165	65.58	Monocline
Tom O'Connor	Frio	5800	177	59.79	Deep Seated Dome Faulted
Colorado	Cockfield	2330	146	35.84	Monocline—Lens
Dirks	Cockfield	3510	149	50.86	Faulted Anticline
Voss	Cockfield	3550	150	50.71	Faulted Monocline
Government Wells	McElroy	1750	128	36.45	Faulted Monocline
Loma Novia	McElroy	1950	138	33.62	Monocline—Lens
Lopez	McElroy	1610	124	36.59	Monocline Faulted
Seven Sisters	McElroy	1900	132	36.53	Monocline Faulted
Greta	Heterostegina	4150	143	65.87	Anticline Faulted
Hilbig	Edwards Lime	3175	116	88.19	Serpentine
Hilbig	Serpentine	2000	121	48.78	Serpentine
Kohler	Mirando	1825	137	32.01	Monocline
Lundell	McElroy	940	111	30.32	Monocline Faulted
N. Sweden	Pettus	4900	179	49.49	Faulted Anticline
O'Connor	Fleming	2950	121	71.95	Deep Seated Dome Faulted
Taft (4000')	Catahoula	3900	133	73.58	Deep Seated Dome Faulted
Taft (4900')	Heterostegina	4750	158	60.89	Deep Seated Dome Faulted
West Texas					
Hobbs	Permian Lime	500	98	27.77	Anticline
White and Baker	Permian Lime	5879	128	129.98	Anticline
Wink	Permian Lime	110	85	22.00	Anticline
North Texas					
Avoca	Palo Pinto Lime	1710	129	34.89	Anticline Faulted

* Based on assumed average Sea Level Temperature of Texas and Louisiana of 80° F.

CURVE 3

TEMPERATURE EFFECTS OF THROTTLING GAS PRODUCED FROM DISTILLATE WELLS



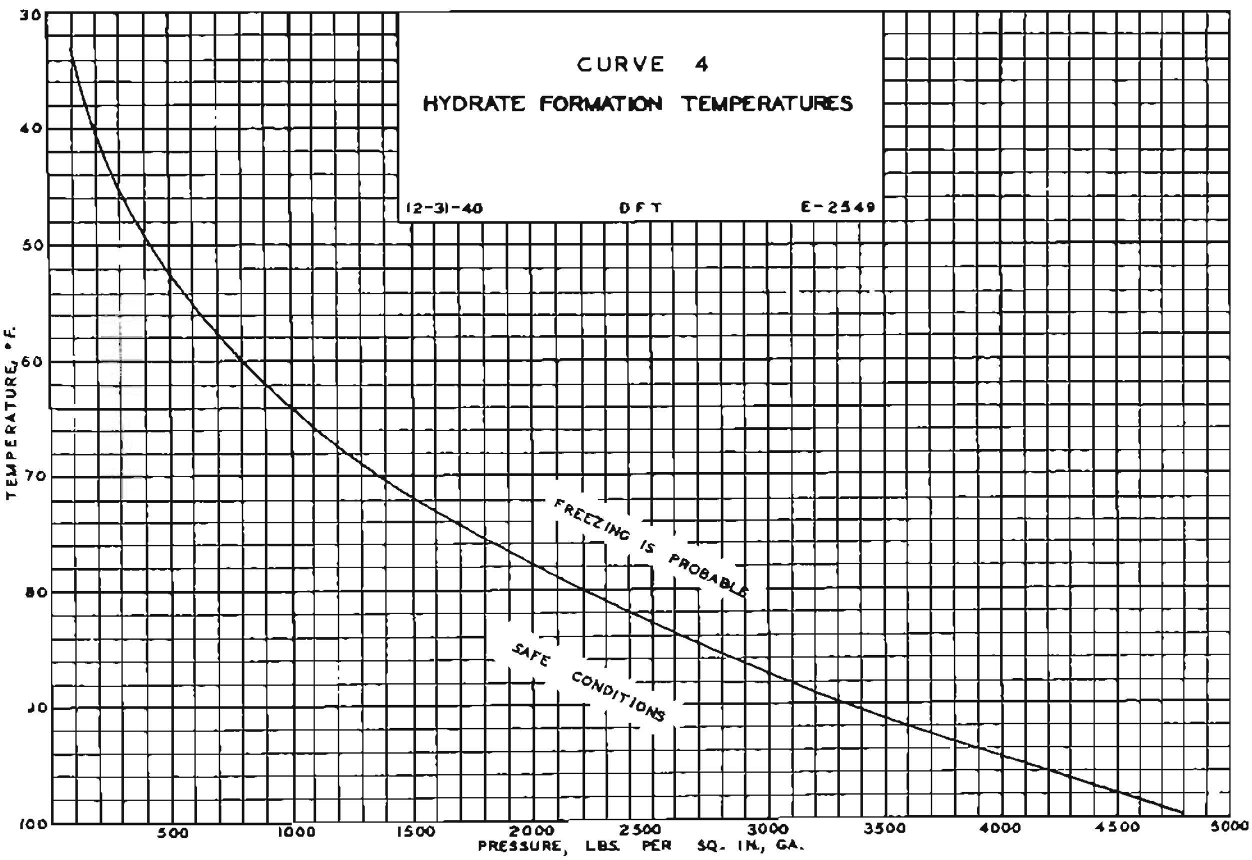

CURVE 4
HYDRATE FORMATION TEMPERATURES
12-31-40
DFT
E-2549
FREEZING IS PROBABLE
SAFE CONDITIONS
TEMPERATURE, °F.
30
40
50
60
70
80
90
100
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
PRESSURE, LBS. PER SQ. IN., GA.

TABLE 5

CORRECTION FACTORS FOR DETERMINING THE PRESSURE IMMEDIATELY ABOVE OR BELOW A BOTTOM HOLE REGULATOR

Instructions:

To determine the theoretical upstream flowing pressure at the regulator before installation, multiply the actual surface flowing pressure (at the desired rate of withdrawal) by the correction factor indicated for the depth at which the regulator is to be set and for the gravity of the gas.

To determine the theoretical downstream flowing pressure at the regulator before installation, multiply the proposed surface flowing pressure by the correction factor indicated for the depth at which the regulator is to be set and for the gravity of the gas.

Well Depth	CORRECTION FACTOR .6 Gravity	.7 Gravity	.8 Gravity
1,000	1.021	1.025	1.029
1,500	1.032	1.037	1.043
2,000	1.043	1.050	1.057
2,500	1.054	1.063	1.071
3,000	1.0645	1.075	1.087
3,500	1.0705	1.089	1.102
4,000	1.085	1.100	1.116
4,500	1.099	1.116	1.132
5,000	1.110	1.130	1.149
5,500	1.120	1.141	1.163
6,000	1.132	1.155	1.181
6,500	1.143	1.175	1.195
7,000	1.155	1.184	1.211
7,500	1.171	1.195	1.227
8,000	1.181	1.210	1.241
8,500	1.190	1.230	1.260
9,000	1.202	1.240	1.273
9,500	1.215	1.250	1.285
10,000	1.225	1.265	1.305

To simplify this operation an average surface pressure of 2200 p.s.i. was used. Using Bureau of Mines Monograph 7 meant extending tables for both depth and pressure.

INTRODUCTION

Ever since the tapping of the first oil and gas reservoir that carried considerable pressure, operators have encountered freezing problems caused by the formation of hydrates on the downstream side of the surface controls. Until recent years, this trouble was merely a seasonal headache that usually started with the first cold spell in the fall. Surface hot water heaters, although troublesome and dangerous, proved to be a remedy for this early trouble, and freezing lines became a seasonal pain and not a serious problem.

During the past few years, however, the discovery of many deep pools has brought to the surface much greater pressures, and has resulted in the need for stronger equipment and safer and better methods for handling this great energy. The control and protection of these reservoirs of energy, as well as the combatting of freezing caused by throttling the production, today constitute problems of great importance, problems that will continue to become more critical as deeper and higher pressure production is found.

The removable subsurface regulator was designed primarily to help solve these problems.

The purpose of this paper is to describe the theory and mechanism of the subsurface regulator, the progress already made by its use, and the important part it is believed the regulator is destined to play in the control of high pressure wells in the future.

EARLY HISTORY OF REGULATOR

Prior to the development of the subsurface regulator, bottom hole choking was used rather extensively to reduce surface flowing pressures and to eliminate freezing. These installations, although they did the job successfully, had one serious deficiency - the choke had a bean with a fixed orifice and only one rate of flow could be had without pulling the choke and changing the size of the bean. Due to the fact that the rates of production sometimes had to be changed frequently to meet varying demands, pulling the choke to change the bean size became, in many instances, quite a task. The operation also required shutting in the well, which was not always convenient.

With the objective of eliminating these deficiencies, work was begun on a removable subsurface regulator. Regulators of several types were built and a series of laboratory and field tests started. The results of most of these were discouraging, primarily because steels suitable for withstanding the abuse caused by chattering, cutting, and corrosion were not available. During these tests of the first forms of the regulator, some of the valve elements became so badly cut by erosion and corrosion as to be useless after only a few days. Other types of valves fluttered and chattered like machine guns; and, in still other types, the valve elements broke into two or more pieces.

It was not until after the tool was redesigned altogether to eliminate chattering, and after the discovery of the resistance of K Monel to corrosion and of Kennametal to flow cutting, that the regulator really began to show practical results.

Because K Monel and Kennametal have played such a vital part in prolonging the life of the regulator, it is proper that these materials be briefly described. K Monel is a corrosion resistant wrought alloy of nickel, copper and aluminum. The metal is non-ferrous but responds very favorably to heat treatment, its hardness being raised from 150 Brinell to 280 Brinell. Its resistance to the action of mineral and organic acids, alkalis, and salts makes it a most desirable material for the regulator valve elements. A very unusual physical property of K Monel is that its heat treatment is distinctly different from that used for steels. The general procedure for hardening this metal is to heat it to 1100 degrees F, and then cool it at a rate not exceeding 15 degrees F per hour. Softening for machinability is performed by heating the K Monel to about 1500 degrees F and quenching in water.

Kennametal is a hard cemented carbide composition most commonly used in cutting tools for machining tough steels. The physical property of this material that makes it so desirable for use in forming the ground seats of the regulator valve elements is its resistance to flow cutting and sand blasting. It was not until after all other materials had failed that the idea of placing Kennametal inserts in the vulnerable sections of the regulator valve elements was conceived. The results of its use were far beyond expectations and it has almost completely solved the abrasion problem. The Kennametal inserts must be ground with diamond-impregnated bakelite wheels and lapped with diamond dust to make a perfect ground seat.

EXPLANATION OF REGULATOR MECHANISM

The removable subsurface regulator consists of two principal parts, the locking mandrel assembly and the regulating assembly. The locking mandrel assembly is the same as has been widely used for removable subsurface chokes and safety valves, and hardly needs a detailed explanation. However, for the benefit of those not familiar with the locking device; as shown in Figure 1, it is a mandrel and slip type lock which may be run and pulled under pressure on an ordinary steel measuring line. Sealing cups are used on the device to effect a shut-off between the mandrel and the tubing. This same locking mandrel assembly has been used in more than 8000 subsurface installations.

The regulating assembly utilizes a spring-loaded "floating" or movable tubular valve seat as the flow controlling element. The design is such that a mechanical load, applied by means of a heavy coiled spring, acts to force the valve seat downwardly toward a closed position; whereas, the differential pressure across the regulator acts against the area of the valve seat to force it upwardly toward an open position. Consequently, two opposing forces are trying to actuate the valve. The mechanical force of the spring and the downstream pressure are acting to close the valve; whereas, upstream or bottom hole pressure is acting to close the valve. Therefore, the position of the valve seat is determined by the prevailing force or forces. Since the mechanical force can be controlled and any desired load impressed on the spring to force the valve closed, a definite and predetermined pressure reduction across the regulator can be had merely by adjusting the amount of initial compression under which the spring is placed.

For example; if a well has a surface tubing flowing pressure of 2500 p.s.i., and it is desired to lower this pressure to 1000 p.s.i., an adjusting ring is used to compress the calibrated regulating spring which will impress a downward load on the valve seat equal to 1500 p.s.i. This force acts to close the valve; consequently, when the tubing gate valve is closed, the pressure above the regulator will build up to slightly more than 1000 p.s.i. and stop, provided there are no leaks in the tubing above the regulator. The valve closes because the forces of the spring load of 1500 p.s.i. and the downstream pressure of slightly more than 1000 p.s.i. overcome the opposing force of the 2500 p.s.i. bottom hole pressure. When the surface choke is opened, the pressure above the regulator gradually pulls down to slightly less than 1000 p.s.i., and the regulator opens. This action is caused by the upward force of the 2500 p.s.i. bottom hole pressure overcoming the downward forces of the downstream tubing pressure and the compressed spring.

The amount the regulator valve opens depends altogether upon the size of the surface choke used. The larger the surface choke, the greater will be the pull down of the downstream tubing pressure; therefore, the differential force across the regulator acting to open the valve will be greater and the regulator valve will be opened wider. Likewise, the smaller the surface choke used, the less the regulator valve will be opened. The operation of the regulator, therefore, is entirely automatic and a variable rate of flow, at a substantially constant low delivery pressure, can be had merely by adjusting the surface choke.

The range of production that can be had through a removable subsurface regulator is ordinarily from zero to 9,000,000 cu. ft. daily; however, the maximum volume is governed by the ability of the well to produce after its flowing pressure has been reduced.

It is the general practice to limit the pressure drop taken across any one regulator to a maximum of 1500 p.s.i. If a greater pressure reduction is desired, two or more regulators are installed at intervals of from 500 to 1000 feet and the pressure drop divided between them. This is done to eliminate, as much as possible, the terrific abuse caused by the abrasive action of flow under differential pressures exceeding 1500 p.s.i.

A complete regulator, having its various parts numbered, is shown in Figure 1. As has been explained, the movable valve seat (15) is forced down onto the valve (17) by the regulating spring (14), which is compressed between the adjusting ring (13) and the valve seat guide (16); and, by the use of adjusting rings of various lengths, any desired differential may be had across the regulator. The chevron packing (12)

FIG. 1

in the valve cage (11) prevents flow around the valve seat and forces all production through its bore. The valve (17) is mounted in the housing (19) and a small valve spring (18), compressed between the valve housing plug (20) and the head of the valve, holds the valve in position for coaction with the valve seat (15). The valve housing (19) limits both the downward travel of the valve seat and the upward travel of the valve.

Under ordinary producing conditions, the valve (17) is held in its uppermost position by the differential pressure and the small valve spring (18), as shown in Figure 1; however, the construction permits the valve to move down to an open position when the pressure above the regulator is greater than the pressure below it. This feature makes it possible to pump downwardly through the regulator should it become necessary to kill the well.

THEORY INVOLVED IN USE OF SUBSURFACE REGULATOR TO ELIMINATE THE FORMATION OF HYDRATES

Hydrates found in the flow lines of high-pressure condensate wells are white, crystalline compounds of water and gas which solidify under pressure at temperatures which are considerably above the freezing point of water. The formation of these hydrates on the downstream side of a choke or regulator is caused by the temperature loss of the flow stream due to pressure reduction and, of course, to the presence of water condensate. The other principal changes in the physical properties of the flow stream due to pressure reduction actually have a tendency to retard the formation of hydrates. These changes of properties are: (a) the increased tendency of water condensate to vaporize under lower pressures, and (b) lowered solidifying temperature of the hydrates. The advantages of these favorable property changes are, however, completely offset and overcome by the prevailing effect of the temperature reduction.

Therefore, the most practicable and satisfactory way to eliminate freezing, or the formation of hydrates, is to raise the temperature of the flow stream before its pressure is reduced, and thus, to compensate the temperature loss due to pressure reduction. Or, conversely, to reduce the pressure of the flow stream at a point at which the temperature of the stream is sufficiently high to compensate the temperature loss due to the pressure reduction.

The two most common methods of eliminating freezing, or the formation of hydrates, involve the use of surface heaters or the installation of subsurface regulators.

Where surface heaters are used, the gas is heated on the upstream side of the surface choke by means of a hot water manifold heated with an open furnace, and the entire pressure reduction is made at the surface.

In wells having subsurface regulator installations, the point of principal pressure reduction is moved from the surface to an underground level, where the upstream gas temperature is sufficiently high to permit the temperature drop that accompanies the pressure reduction without the formation of solidified hydrates. Actually, both methods accomplish the same result; however, the subsurface regulator takes an economical shortcut by utilizing the inexhaustible natural supply of earth heat to achieve the desired result.

Determining the minimum depth at which the regulator can be set to completely eliminate freezing is the only problem of any importance connected with the use of a subsurface regulator. Since formation pressures increase with depth, the principal problem is to select a depth that provides a temperature adequately high to allow the loss in heat caused by the pressure reduction across the regulator without solidification of the hydrates.

Sufficient data and formulae are now available to determine whether freezing is likely to occur when a certain pressure reduction is made at a certain depth. To make the computation, it is necessary to know the following:

1. Temperature gradient of well.
2. Gravity of flow stream.
3. Upstream and downstream flowing pressures at regulator.
4. Temperature loss through regulator.
5. Temperature and pressure conditions favorable for the formation of solidified hydrates.

The procedure customarily followed is:

1. Decide upon the surface flowing-pressure and the rates of flow desired. This determination will, of course, be affected by the gathering system line pressure.
2. Determine the upstream and the downstream flowing-pressures at the depth at which the regulator is to be set.

Table 5 has been compiled for use in determing the theoretical upstream and downstream pressures across the subsurface regulator before it has been set. The upstream pressure, which will be present immediately below the regulator, is calculated by multiplying the actual surface flowing pressure (before the regulator is installed) at the desired rate of flow by a correction factor determined for the depth at which the regulator is to be set and for the gravity of the gas. The downstream pressure immediately above the regulator is found by multiplying the proposed or desired surface flowing-pressure by the same correction factor.

3. From the upstream and downstream flowing pressures determined in step 2, the pressure reduction to be made by the regulator is calculated.

Subtracting the downstream flowing-pressure from the upstream flowing-pressure will give the pressure reduction which the regulator must be adjusted to make. A calibration chart for the regulating spring will indicate the size of the adjusting ring which will give the desired pressure reduction.

4. Determine the upstream temperature of the flow stream at the depth at which the regulator is to be set from the temperature gradient of the well.

TABLE 2

Table 2 lists the bottom-hole temperature and temperature gradient of the principal fields throughout Texas and the Gulf Coast. Temperature gradients are expressed in feet per one degree F increase in temperature, and are readily calculated by dividing the total depth of the well by the temperature range, determined by subtracting the mean annual temperature (80 degrees F) from the bottom-hole temperature.

5. Using the pressure reduction found in step 3 and the upstream flowing pressure, determine the resultant temperature drop at the regulator.

CURVE 3

Black, Sivalls and Bryson's curve, entitled "Temperature

Effects of Throttling Gas Produced from Distillate Wells", Figure 3, contains the best data yet found on temperature loss due to pressure reduction. This curve has proven consistently correct and in good agreement with other observed data. Using the known determinants, it is possible to find from the curve the temperature reduction of the gas as it passes through the regulator.

6. Subtract the temperature reduction, just determined, from the upstream temperature of the flow stream, determined in step 4, to find the downstream temperature of the flow stream.

7. Knowing the downstream temperature of the flow stream and the downstream flowing pressure just above the regulator, determine the probability of freezing.

CURVE 4

Hammerschmidt's curve, Figure 4, on Hydrate Formation Temperature, provides probably the most widely used data for determining the temperatures and pressures favorable for the freezing of water condensate in flow lines. Using the known determinants, it is possible to determine from this curve the probability of freezing, or the formation of solidified hydrates.

If freezing is indicated, either a lower depth with its correspondingly higher temperature should be chosen for setting the regulator or, if such is impossible or impracticable, the pressure reduction should be divided between two or more regulators set at intervals of from 500 feet to 1000 feet apart in the well. This spacing permits the earth heat to raise the temperature of the flow stream between the points of pressure reduction, to compensate the heat loss incident to each succeeding reduction of pressure.

As an extreme example; in one installation in West Texas, where bottom-hole temperatures are abnormally low, even a very small pressure reduction was sufficient to cause freezing when the entire drop was taken across a single regulator. After dividing the desired pressure reduction between two regulators, staged at intervals of 500 feet, freezing was completely eliminated.

IMPORTANT CONSIDERATIONS IN ADJUSTING REGULATOR FOR DESIRED FLOWING PRESSURE

The two most important factors to be considered in determining the adjustment of a regulator required to give a desired surface flowing pressure are:

1. The maximum rate at which the well is to be flowed, and the natural "pull down" of the flowing pressure at this rate of flow.

2. The change in the weight of the flow stream column above the regulator due to pressure reduction.

The "pull down" of pressures is directly dependent upon the productivity factor of the well and is particularly important where wide variations are to be made in the rate of production. If the well has the capacity to produce at the maximum rate, as well as at the minimum rate, without an appreciable change in the flowing pressure at the surface; then, this factor can be neglected. However, if the well surface flowing pressure drops several hundred p.s.i. when the well is flowed at the maximum rate; then, this factor is most critical and must be taken into consideration in determining the proper delivery or surface flowing pressure.

The "pull down" pressure drop is neither absorbed nor retarded by the regulator installation; consequently, this drop must be added to that caused by the regulator, and cannot be ignored in adjusting the regulator to obtain the desired pressure reduction.

For example; if a well flows one million cu. ft. per day at a surface flowing pressure of 2500 p.s.i., and three million cu. ft. per day at a surface flowing pressure of 2000 p.s.i.; and, it is desired to lower these pressures 1500 p.s.i.; then, the corresponding flowing pressures will be 1000 p.s.i. and 500 p.s.i. respectively. However, if the gathering system should carry a line pressure of 500 p.s.i. or higher, then it would be impossible to produce at the rate of three million cu. ft. per day because the surface flowing pressure would not be sufficiently high. Therefore, in order to make this higher volume available, it is necessary to decrease the pressure reduction for which the regulator is to be adjusted. If the pressure drop across the regulator is reduced to approximately 1200 p.s.i., the flowing pressures become 1300 p.s.i. and 700 p.s.i. respectively, and the maximum rate of flow can be had. These surface flowing pressures, although slightly higher than first desired, are adequately high to cause flow into the 500 p.s.i. gathering line, and yet are sufficiently low to prevent freezing at the surface choke. Therefore, in wells in which the flowing pressures have a tendency to "pull down", it is sometimes necessary to sacrifice maximum pressure reduction in order to have high volumes of flow available.

To determine the correct adjustment of the regulator for producing the desired surface flowing pressure, the weight of the column above the regulator must be considered. This is necessary in order to determine the upstream flowing pressure immediately below the regulator and the downstream flowing pressure immediately above the regulator. These determinations are necessary because these pressures, together with the regulating spring, actuate the regulator valve. As has already been explained, the pressures may easily be determined by use of Table 5. Knowing the theoretical upstream and downstream pressures at the regulator, it is a simple task to subtract the downstream pressure from the upstream pressure to determine the pressure reduction for which the regulator should be adjusted. A calibration chart for the regulating spring is used to indicate the size of the adjusting ring which must be used to secure this particular pressure reduction.

RESULTS

The primary objective of the subsurface regulator was to provide for variable rates of flow under conditions which would eliminate freezing in flow lines and reduce dangerously high surface flowing pressures to safe workable limits.

This objective has been successfully and completely attained.

In many instances, the use of expensive and elaborate surface heaters has been entirely eliminated by the simple installation of one or more subsurface regulators. Surface flowing pressures ranging up to 5000 p.s.i. have been reduced to 1500 p.s.i. and less. In all cases, the maximum flowing pressure has been removed from the surface connections or controls to a safe subsurface depth of several thousand feet. It was principally for these purposes that more than three hundred and fifty subsurface regulators were installed in less than two years.

Other results, such as the reduction of condensate ratios and retarding of water encroachment, have been considered incidental or subordinate and have not been given the amount of attention they deserve.

In most cases in the past, the subsurface regulator installations have not materially affected condensate ratios, although several cases in which there was an increase in condensate recovery have been observed. These increases might possibly have been due to the long distance between pressure reduction stages; that is, between the subsurface regulator, the surface choke, and the separator. Or, a combination of the lengthy travel with varying conditions of temperature and pressure existant between these stages may have been favorable for condensate precipitation.

To the writer's knowledge, no subsurface regulator installation has been made for the single purpose of increasing condensate recovery; consequently, the effects on the ratios were obtained accidentally and were not precalculated. However, it is believed that it may be possible, through the use of one or more subsurface regulators, to establish the temperature and pressure conditions in the tubing which would be most favorable for the "dropping-out", or precipitation, of condensate and, therefore, to provide for most efficient condensate recovery.

In practically all installations, it has been noticed that the regulator has stabilized ratios to a great extent. This has probably been caused by the maintenance of a relatively constant bottom hole pressure, which could not be pulled lower than the amount of pressure differential for which the regulator was adjusted. At least the same amount of pressure as the differential for which the regulator is adjusted must be present below the regulator before the regulator valve can be opened.

CONCLUSIONS

Since the first removable subsurface regulator went on the market, less than two years ago, more than 350 successful installations have been made. These installations were made in 103 different fields, including practically every high pressure field throughout the world. The rapid acceptance the industry has given this new method of pressure control convinces the writer that subsurface control is yet in its infancy, and that it is destined to play a still greater role with the advent of still deeper production and higher pressures.

While the data presented here are very general, they are sufficient to give the operator a practical conception of the changes in the physical properties of the flow stream caused by subsurface pressure reduction; and, have already proven to be of great value in the installation and use of subsurface regulators in the various fields.

It is the writer's hope that this paper will encourage further technical reserch relative to the use of subsurface regulators for the control of temperatures and pressures in the well flow string to obtain conditions most conducive to condensate precipitation, and, therefore, to greater and more efficient recoveries of condensate.

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