089

A Dynamic Pulsing Workover Technique for Wells

MAURICE B. DUSSEAULT, T.J.T. (TIM) SPANOS, BRETT C. DAVIDSON

PE-TECH Inc., Box 21028, Lloydminster, Alberta, T9V 2S1

Abstract

A new approach to workovers based on high-amplitude pressure pulsing was developed in 1998, and introduced in the Canadian heavy oil industry in cold heavy oil production wells. The method uses a downhole hydraulically actuated piston-and-cylinder principle to suddenly force a volume of liquid through the perforations, into the near-wellbore region. A pressure pulse is applied every 20-60 seconds for a period of 45-120 minutes, stopped for 15 minutes, then recommenced. After the cycles are repeated for 8-24 hours, the well is placed back on production. A great deal of kinetic energy is introduced into the system, generating coupled porosity pressure waves. These lead to opening of perforations, destruction of local and inter-well stress arching that can inhibit sand movement and liquid flow, dislodgment of fine-grained particles such as clays or asphaltenes, liquefaction of the reservoir sand, and in many cases has led to substantial pressure increases. These effects have beneficial consequences on well production, allowing renewal of liquid flow. Energy analyses and typical pressure-time treatment records are presented. A reasonable success ratio exists and is improving, based on better candidate screening and understanding of the consequences of pressure pulsing.

Introduction

Cold Heavy Oil Production (**CHOP**, please note a companion paper in this conference [1]) has become a viable IOR approach in heavy oil reservoirs in shallow (<1000 m) unconsolidated sandstones ($\varphi \approx 0.30$). Because oil rates are linked to continued sand influx, it is necessary to initiate sanding, maintain free sand flow, and re-establish sand flow if it ceases. Sand flow is maintained by two energy sources: gravitational energy associated with overburden stresses and displacements, and fluid-phase drive energy. The latter is related to liquid pressures and the effects of gas exsolution in maintaining these pressures through the creation of a bubble phase (foamy flow) rather than a continuous gas phase.

A considerable amount of the energy to maintain CHOP can be extracted from the gravitational stress field through small downward movements of the overburden. For example, consider a CHOP well at a depth of 650 m ($\sigma_v \approx 15$ MPa) with 300 m rectangular spacing. Over the life of the well, if the overburden moves down by one meter, the work per well performed on the reservoir is $W = F\,d = \sigma_v\,A\,d \approx 1.5\times10^{12}$ N m (1.5 TJ). The physical realization of this work is in overcoming frictional resistive forces, aiding the sand to yield and flow, which helps generate zones of enhanced permeability around wells. If the reservoir is naturally compactive, this energy also forces oil from the pores (compaction drive).

Similarly, the work that can be done by gas expansion in a CHOP process is far greater than in a conventional oil reservoir. In the latter case, a continuous gas phase is created soon after drawdown exceeds the gas bubble point; instead of displacing oil to the wellbore, the gas-oil ratio (GOR) rises, oil production drops, and the potential gas drive energy is rapidly exhausted. In the case of CHOP processes, the foamy oil behavior is highly beneficial; bubbles develop and grow without coalescence, driving more fluid and sand to the wellbore. Furthermore, no continuous gas phase is formed, thus far-field pressure depletion is greatly retarded. This often leads to a GOR in a CHOP well that remains approximately constant for long periods of time.

Excluding equipment failures or plugging of the wellbore or pump, sand influx into a CHOP well may decline or cease for one or more of the following reasons [2]:

1) The perforations may become blocked by stable sand arches or chunks of rock or cement.
2) In the near-wellbore region, the sand may become recompacted, arching successfully to resist the viscous drag forces associated with production.
3) The well may become disconnected from the far-field (>50 m) pressures extant in the interwell region, reducing pressure gradients and eliminating the viscous drag forces that help drive CHOP.
4) In the far-field, the interwell regions may successfully carry the overburden (large-scale arching) and resist further destabilization, thus eliminating the gravitational forces that help drive CHOP.
5) The entire reservoir may be so depleted that it is no longer possible to mobilize sufficient energy to maintain sand flux to the producing wellbore.

With the exception of the massive and complete depletion case, it is generally possible to re-establish CHOP well productivity through various workover techniques. The most successful techniques appear to be those that apply a large perturbation force to the reservoir fabric, so that perforations are opened, recompacted sand liquefied, and the gravitational and pressure driving forces re-established.

Workover Methods in CHOP Wells

When a well becomes blocked with sand and the pump must be withdrawn, sand cleaning is often carried out by wireline bailing. This process entails repeated dropping of a long cylindrical tube that eventually becomes partially filled with sand. It is then withdrawn, emptied, and the process repeated until the sand level is lowered beneath the perforations, at which time the pump is re-installed. If the fluid is too viscous for the bailer to be effective, an operator can add diesel (or other blended oil) to lower the viscosity to allow the bailer to drop without "floating". The repeated aggressive dropping of the sand bailer has a small beneficial effect in generating small surges in the near-wellbore region, helping to unblock local arching effects. A work estimate for bailing indicates that little energy is input to the reservoir; viscous friction and frictional dissipation during sand impact consume most of it. The cross-sectional area of the bailer (~_" wall thickness for a typical 3_" diameter bailer) does not act as a full piston, as casing fluid rushes by the bailer as it is dropped. The mass (~200 kg) is low, and the kinetic energy is consumed by the plastic (frictional) flow of sand into the bailer. Also, the actual drop height of the bailer is low (~2 m) and this affects the energy, which is estimated to be less than 0.5 MJ even for long-term bailing.

A "super-flush" consists of aggressive injection of ~10 m^3 of oil (sometimes hot oil or oil with a surfactant) through the perforations. The goals are to create a surge that unblocks perforations and pushes away the sand from the near wellbore, to dilute the sand-oil slurry in the near-wellbore region, to reduce the viscosity (hot oil), and to reduce capillary forces that may be aiding in the stabilization of sand arches. Work calculations in a super-flush are problematic because of viscous friction losses through the tubulars and perforations, combined with incomplete knowledge of boundary conditions. We estimate that the energy input in a superflush is much less than 1 MJ.

Perforating causes severe damage to the formation sand near the well, which is beneficial, as it helps destabilize the sand to initiate CHOP. High-energy perforating (>40 g explosive per charge, 39 charges per metre, 2-4 m of charges) is routinely used, along with large diameter entry ports to reduce sand arching tendencies. Re-perforating an old well, which was usually perforated with smaller diameter and more widely spaced charges, is a useful means of re-initiating CHOP, or turning a non-CHOP well into a CHOP well. Slotted liners and screens can also be perforated to convert to CHOP production. Although most of the energy is consumed in penetrating the steel and the near-wellbore region, the large perturbation can destabilize the sand out to a distance of perhaps a metre or two. Therefore, it has a beneficial effect in re-initiating sanding. Energy transfer to the medium cannot be calculated directly, but on the order of 0.5-2 MJ seems to be the upper limit.

Chemfrac™ is a process involving downhole detonation of a rocket propellant charge. The detonation creates a short time but high-pressure pulse that forces wellbore liquid through the perforations at high velocity and applies a shock wave to the near-wellbore region. In CHOP wells it is used specifically as a means of unblocking perforations and re-liquefying the region around the well, and seems quite effective. Unless tubing conveyed, these treatments usually have a full column of fluid above the charge to prevent it from blowing upwards out the top of the well. It appears that a full hydrostatic fluid column assists the process in propagating outwards into the reservoir. If there is free gas in the system, it acts as a shock absorber, spreading out the rise time of the pressure impulse applied to the formation. The energy applied to the stratum and well is the chemical energy released during propellant burn, generally 6.5 MJ for a typical 10 m charge length.

The Pressure Pulse Workover Approach

The pressure pulse technique (PPT™)[1] involves repeated applications of large pressure pulses through sudden displacement of liquid in the wellbore. This is accomplished by a down-hole positive displacement process, with the activating tool located as near to the perforations as possible. The casing is used as the cylinder, and a piston, actuated by the service rig (direct mechanical impulse) generates a sudden displacement of the liquid. Typically, an 8 m stroke is executed in a 7” (178 mm) hole, displacing a liquid volume of 0.2 m^3 (~1.25 BBL) per stroke. Different impulse volumes arise in different diameter casing, and the stroke length can be varied, although the maximum stroke is almost always used.

The sharp downward stroke of the tool (in 2.5-5 s, with a rapid initial rise time) is followed by a dwell period (3-10 s) at bottom to allow hydraulic energy transfer through pressure dissipation from the wellbore vicinity. Then, the tool is lifted at a modest velocity, from 0.25 to 1 m/s, to its upper position; typically, this return stroke takes 20-35 s. This gives a full cycle time of 30-60 s for each impulse.. A PPT™ workover is carried out in “stages” by stroking for ~45-120 min, then stopping for ~15 min (called a “station stop”, Fig 1). At the end of the station stop, the fluid level in the annulus is measured acoustically, additional liquid may be added to the casing (now or during the active pulsing), and stroking is continued. A PPT™ workover will typically last 6 - 12 hours if the primary goal is to unblock the well and re-initiate sand influx. Stroking for shorter and for longer times has been tried to try and optimize the process and study the consequences on well behavior.

During the re-stroking period, charge liquid can enter the cylinder from the formation through the perforations or from the casing liquid through flow between the tool and the casing on the upstroke

[1] Pressure pulsing methodologies and tools for workovers, full-scale reservoir flow enhancement, and other applications to porous media are Patent Pending.

only. The proportion of liquid influx from the casing is called the volumetric efficiency, and can vary from 0% if the casing is almost empty, to close to 100% if desired. The volumetric efficiency depends on the head of liquid in the casing above the tool, the formation pressure, the degree of perforation opening, and the viscosity of the liquids in the casing and flowing back through the perforations. *A priori* calculations of volumetric efficiency are only approximate, but the casing liquid level measurements taken at every station stop allow average efficiency to be calculated precisely. The volumetric efficiency is often deliberately varied over the PPT™ workover duration, in order to achieve the specific goals desired, and in response to the pressure reaction measured in the tool. In a typical workover of a CHOP well at 500-700 m depth, from 5 to 25 m^3 (largest volume used to date was 40 m^3) of fluid is introduced through the casing. Assuming that a total of 500 strokes are used, this is a volumetric displacement efficiency of 5-25%.

It is not necessary to introduce charge liquid to achieve perforation unblocking and near-wellbore liquefaction; the large impulses will suffice. Fig 2 is a case with no charge liquid added for the first 4.5 hours, when a small volume was added. (We believe this is evidence of unblocking and liquefaction of the sand around the well, giving less perforation flow resistance, and therefore less amplitude.) However, to propagate the process far into the reservoir, liquid introduction is beneficial. Also, if the goal of the workover is to place a well-dispersed specific workover fluid in the near-wellbore region, the PPT™ approach will first be used to unblock the perforations and wellbore region. This may take two station stops; then, the workover liquid is introduced at the desired rate, and perhaps even chased with a compatible fluid to increase reservoir contact volume.

Work Calculations and Monitoring

The work performed during the workover can be estimated in two ways: by a direct work calculation (W = **F** d) because the mass of the steel goods is known and the tool is mechanically actuated; or, by integrating the pressure curve over the impulse period, using the area of the casing: $(W = p(t)Adl)$. Comparison of the two allows an estimate of energy input and efficiency. Consider a 2000 kg mass (~tool and tubing mass for a 600 m deep well) falling 8 m. Work is 2000 8 **g**, ~0.16 MJ, and repeated for 500 strokes, this gives about 80 MJ of energy. Integration of the pressure data suggests that energy transfer efficiencies of ~10-65% are commonly achieved.

BHP below the tool is measured by a pressure gauge connected to a surface laptop computer via wireline cable. Fig 2 is a pressure vs. time trace for the BHP during a typical workover. Individual strokes are not shown here; only the range of the maximum and minimum pressures are drawn. Minimal fluid was added to the annulus during this workover because the fluid level in the well was very high initially (hence the BHP of 400 psi), and stayed high during the workover.

Fig 3 shows temperature response curves for two different PPT™ workovers (the upper curve is for the same workover shown in Fig 2). In the case with a substantial temperature rise, no liquid was fed into the casing during the workover. Temperature rise reflects frictional energy losses through the casing-tool contact on the downstroke, and heating as liquid is forced through the perforations and drawn back into the casing on each stroke. If liquids are fed into the annulus during the workover, heat is carried away and a different temperature response is observed. This is shown in the lower curve where, after an initial small temperature rise during the first pulsing period, charge liquid was slowly trickled in during the workover, carrying the heat away into the reservoir.

Mechanisms

The hydraulic energy during each stroke is transmitted across the perforations to the reservoir, where it has several important effects. The sharp impulse generates a temporary steep outward gradient that forces blocking material away from the perforations by a hydrodynamic force that, for a fragment of area A, can be expressed as $I = A\Delta p\Delta t$; this generates a force acting coaxially with the gradient direction. However, a single impulse, or several impulses, may be insufficient to overcome restraining frictional forces, especially if effective normal forces (frictional strength) restrain the fragment. The impulse increases the pore pressure behind the casing, reduces these restraining forces, and leads to liquefaction of the immediate wellbore region if the material is granular and without cohesion. If the reservoir is cemented and there are pore blocking minerals or asphaltenes, these particles are loosened by the periodic impulses, reducing mechanical skin effects.

Fig 2 is a case of unblocking the well. For the first ~1.5 hours (from 1 to 2.5 hours on the time axis) wide pressure swings, particularly the low pressures recorded during the slow upstroke, are evidence that fluid flow is impaired. These swings were all on the order of 400-450 psi amplitude. Over a short period of time, from 2.5 to 3 hours, the amplitude collapsed to about 50-80 psi, and this trend continued for the rest of the workover, indicating a greatly reduced flow resistance: the well was unblocked by the PPT™ workover.

Introduction of liquid on each stroke can accelerate the process of liquefaction that occurs around the wellbore, and is used when there is a lower fluid level in the well. In the case of CHOP wells, liquefaction means that sand flow is more easily re-initiated after the workover. However, there is another physical effect. A volumetric dilational wave of a diffusional nature is generated (a porosity diffusion wave [4]) and propagates at a slow velocity (10-50 m/s) through the poorly consolidated medium. Theoretical [5], laboratory [6] and field work [3] have shown that this leads to an increase in fluid flow rate or pressure, depending on boundary conditions.

The change in pressure and the mechanical perturbations themselves can propagate substantial distances in the reservoir. In several field cases where the casing liquid levels or the production behavior of offset wells (250-350 m) were measured after a PPT™ in one well, beneficial changes were observed, indicating a small amount of renewed energy at the offset wells. Clearly, a 9-12 hour PPT™ can affect a large reservoir volume. We hypothesize that another important effect is the re-activation of gravitational drive energy for the CHOP process. The stable inter-well "pillars" that develop are perturbed, and this allows the overburden to once again move downward and aid in stress-driven plastic sand flow. We make the analogy to earthquake processes, where long-term repeated large-amplitude perturbations of low frequency are needed to liquefy sands; short duration shaking or small amplitude perturbations seem insufficient to achieve liquefaction. This seems to be the case for reservoir excitation: typical small-amplitude seismic excitation is ineffective, whereas prolonged large-amplitude pressure pulsing is effective.

Geilikman et al. [4] hypothesize that the porosity diffusion waves may trigger sympathetic seismicity in cases where the stresses are near the point of rupture. Because of the dynamic stress re-distribution associated with CHOP, there will always be zones some distance from the wellbore that are near the shear yield limit, and the perturbations induced by the pressure pulsing can trigger their rupture, helping re-establish the gravitational energy component of the process. The "stable pillars" are destabilized, and this may also help reconnect the well to undepleted pressures existing in this interwell region.

Examples of Pressure Pulse Workovers

The cases shown in this article are in ~30% porosity unconsolidated sandstones with heavy oil from 1200 to 20,000 cP in situ viscosity. Depth ranges from 450 m to 850 m, and reservoir thickness from 4.5 m to as large as 30 m.

The well in Fig 2 had never been successfully placed on sustained production as a CHOP well. The operating company hypothesized that drilling or cementing damage prevented the sand from becoming destabilized and flowing into the wellbore for CHOP production. After the workover, the well has produced for several months at a rate of 6-8 m^3/day, which is a reasonable rate for a CHOP well. No liquid was added to the well during the workover, therefore the increase in pressure observed must arise from the porosity diffusion process and related mechanical effects.

Fig 4 is the pre-PWT™ and post-PWT™ production behavior of a shallow (450 m) heavy oil well in Alberta. At the time of writing, production at 8 m^3/d was being sustained, and sand appeared to be flowing into the wellbore unimpeded, allowing the high oil rates to be maintained.

Fig 5 is a case where an 800 m deep well in Saskatchewan had never produced economically. Several large placements of compatible oil took place during the workover, resulting in a sharp climb in the formation pulsing response (p_{max}-p_{min}).

Fig 6 is a well adjacent to the Cold Lake Oil Sands area in Northern Alberta, showing a sudden increase in the response amplitude after some fluid had been trickled into the well. In this case, we believe that the fluid introduction eventually helped to drive gas back into solution around the wellbore. Both of these cases resulted in renewed or improved well production, despite modest permanent pressure increases.

Overall, about 38 workovers had been completed at the time of writing. Almost all were technical successes, and it appears that most were economic successes as well (estimated 60%). Screening procedure evolution is expected to increase this ratio, but we have noted a tendency in the operating companies to use this new method on “hopeless” wells. Substantial successes have been achieved in wells that never were successfully placed on CHOP production, but we do not advocate the process for “hopeless” cases.

Energy Introduced into the Reservoir During a Pressure Pulse Workover

The energy applied during a workover is a useful measure: this energy can in principle change the reservoir state or become accessible as enhanced flow potential. It is difficult to calculate reliably how much of the energy generated in any specific workover method is transmitted to the reservoir behind the casing because the pressure changes are not measured.

Assuming that once the perforations are all opened (e.g. after 2.5 hr in Fig 2) their resistance to flow does not consume a large fraction of the Δp, the pressure in the cylinder seems to be a reasonable (upper-bound) estimate that can be used to calculate energy efficiency. This leads to the energy input curve in Fig 2, as well as the two cases shown in Figs 7 and 8. Fig 7 is a case of massive reservoir depletion; the well had already produced a great deal of heavy oil, and had experienced a loss in production rate. The workover never succeeded in pressurizing the near-wellbore environment, and pmax-pmin was never higher that 60 psi (less than 20 psi for the final six hours). Nevertheless, the well did produce better after the workover, likely because the perforations were unblocked (at the period 1.5-2 hrs), but this case was probably not an economic success (six months post-PWT™ well behavior is not yet availabe). The energy transfer efficiency was less than 10% of the theoretical possible, as the reservoir took all the fluid immediately, affording no resistance whatsoever.

Figure 8 shows a case where over 50% efficiency was achieved, and the PWT™ was quite successful in building up the well pressure and helping re-establish well production. We note that when PWT™ is used on a non-depleted well, it seems particularly effective at pressure build-up and well production establishment, therefore it should be considered as part of well completion strategies for CHOP wells.

Compared to other workover methods, PWT™ introduces much larger amounts of energy in a suitable form over a reasonable time period. What happens to this energy? Some is consumed in viscous friction, some goes to remold and liquefy sand (probably limited to 5-15 m around the wellbore), and the rest is evidenced as generated waves (dominantly the porosity diffusion wave) or as an enhanced pressure. As in any diffusional process, the amplitude of a perturbation, be it a pressure pulse or a strain wave, decays because of radial spreading and attenuation. If the wellbore is surrounded by liquid, the efficiency of porosity diffusion wave generation is far greater than if free gas is present. Thus, if it is an option, repressurization will help increase the efficiency of the energy propagation, and it can then be dispersed farther out into the reservoir, with attendant positive effects.

Discussion

The PPT™ workover is effective but is not a panacea for all well problems. Experience is currently limited to CHOP wells, and well evaluation parameters (screening criteria) are now evolving.

If a well is massively depleted, to the point that the perforations are on vacuum (which occurs occasionally in CHOP wells), the problem is not blockage, but general reservoir energy loss; an example was given in Fig 7. It was not possible to apply large amplitude pressure pulses because the well simply took fluid easily at whatever rate it was introduced.

Cases with a great deal of low-pressure free gas behind the casing are also poor candidates because the gas severely attenuates the pulse amplitude. This makes it difficult to transmit the effects any substantial distance beyond the casing. In some reservoirs, low pressures may be related to an exceptionally low bubble point, so low that the foamy oil enhancement mechanism does not develop. Otherwise, if the well developed an interconnected gas phase during production, the solution gas may simply have been depleted. Less success has been achieved in cases where the well has experienced a long and successful production history, even if there was originally a well developed foamy oil phase. This is also linked to generally low energy left in the reservoir and the presence of large volumes of free gas.

There is substantial geological heterogeneity in the fluvio-deltaic strata of the wells that have been stimulated to date (nine different oil fields with a wide range of properties). If a well is drilled into a levee or bank overspill deposit with a great deal of clay streaks, successful CHOP production is problematic (as are other production technologies). The PPT™ approach may help in breaking down the impediment, but there is a high risk that the well will simply demonstrate a rapid drop in production rate after the workover. High clay content zones or sections with many shaley streaks are considered poor candidates.

On the positive side, the PPT™ workover method will be effective in cases of mechanical skin, as the large perturbations unblock pore throats and release clay particles and asphaltenes. Simply reversing the gradient, as in a conventional injection workover, is usually not sufficient to destroy the source of mechanical skin; the repeated aggressive pulsing not only unblocks pore throats, but helps disaggregate clumps of clay minerals and asphaltenes that have clustered together.

Experimental work and exploration of the mechanisms in pressure pulsing leads to the conclusion that the introduction of a workover liquid under aggressive pulsing leads to better dispersion in the near-wellbore region. The periodic and large alterations in gradient tend to suppress channeling and long-distance fracture propagation. On the input stroke, these features propagate short distances, but partially heal and flow back on the slow upstroke. The next downstroke will tend to contact more new reservoir material because of this, and this effect accumulates as the pulsing continues. Because the volume of each stroke is a maximum of one barrel, there is little potential for long-distance propagation of channels or fractures. The volumetric efficiency can be altered during the workover to maximize this effect.

It appears that the PPT™ workover is a better way of introducing liquids such as chemicals and diluents, compared to a conventional injection workover. In a typical case to introduce a chemical treatment liquid, a sequence such as the following might be recommended:

1) Execute 1-2 hours of PWT™ pulsing to open perforations and dislodge pore-blocking materials. This may take place with compatible fluid input.
2) Begin introducing the workover liquid slowly, using a low volumetric efficiency rate.
3) Terminate workover fluid introduction, and continue pulsing for 1-2 hours to maximize contact and dispersion in the near-wellbore region.

Summary

A new workover approach based on high amplitude pressure pulsing has been developed. It has proven to be effective in many cases in re-establishing heavy oil production from cold heavy oil production wells. The method appears to have applications in workovers in conventional oil wells. However, as with any workover method, candidate wells must be screened carefully, and the goals of the workover must be clearly defined so that the usefulness of the approach can be optimized.

References

[1] Dusseault, M.B., El-Sayed, S.: CHOP - Cold Heavy Oil Production, Proc. 10th EAGE European Symposium on IOR, Brighton, England, August (1999).

[2] Dusseault, M.B., Spanos, T.J.T., Davidson, B.C.: A New Workover Tool: Applications in CHOP Wells, Proc. 50th Annual Technical Meeting, Petroleum Society of CIM, Calgary, Alberta (1999)

[3] Spanos, T.J.T, Davidson, B.C., Dusseault, M.B.: Pressure pulsing at the reservoir scale: a new IOR approach, Proc. 50th Annual Technical Meeting, Petroleum Society of CIM, Calgary, Alberta (1999)

[4] de la Cruz, V., Sahay, P.N., Spanos, T.J.T.: Thermodynamics of porous media, Proc., Royal Society of London, A 443, 247-255, (1993).

[5] Wang J., Dusseault M.B., Davidson B.C., Spanos, T.J.T.: Fluid enhancement under liquid pressure pulsing at low frequency, Proc. 7th Unitar International Conference on Heavy Crude and Tar Sands, Beijing, PRC, October (1998).

[6] Geilikman, M.B., Spanos, T.J.T, Nyland, E.: Porosity diffusion in fluid-saturated media, Tectonophysics, , 217, 1/2, 111-115 (1993).

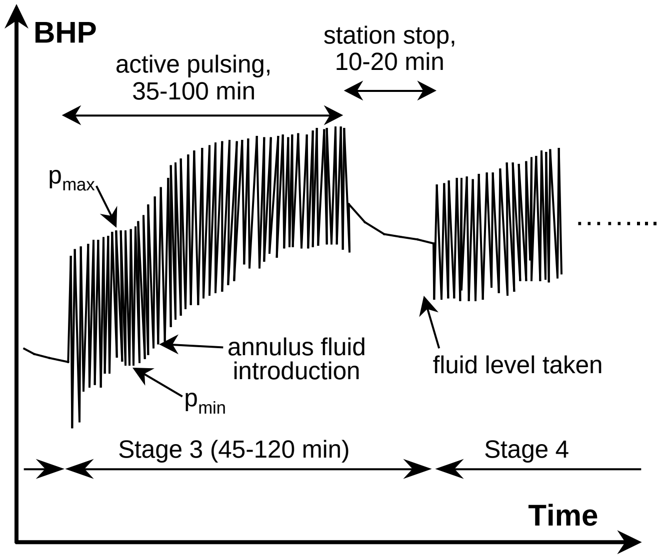

Fig 1: “Stages” in a pulsing workover

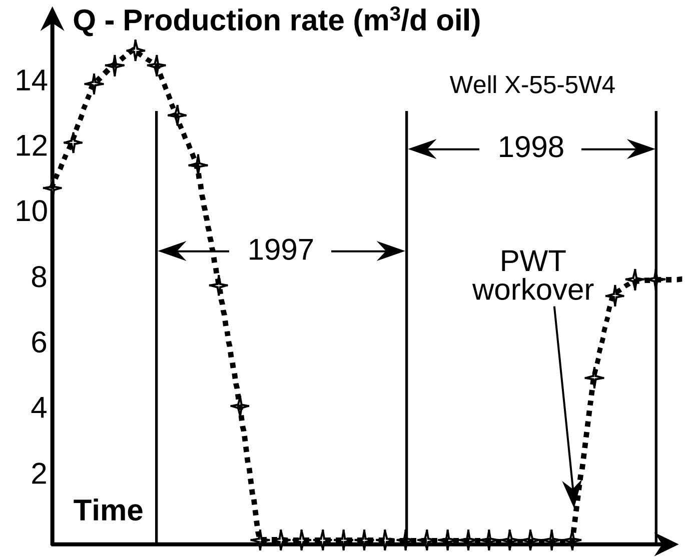

Fig 4: Q-t response for Well X-55-5W4

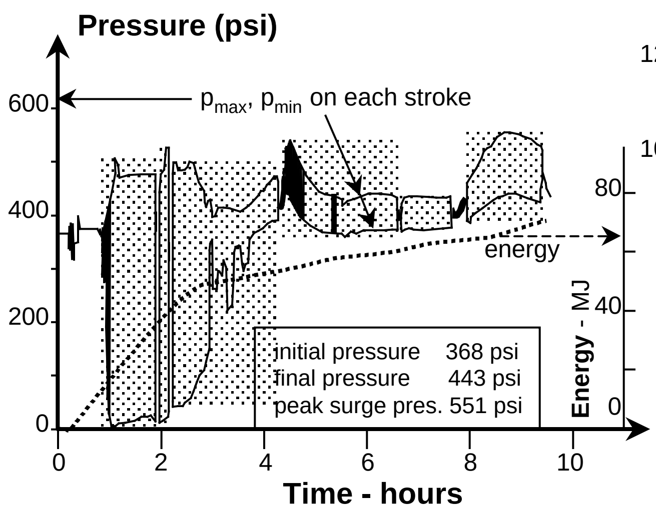

Fig 2: P-response curve - Well #1

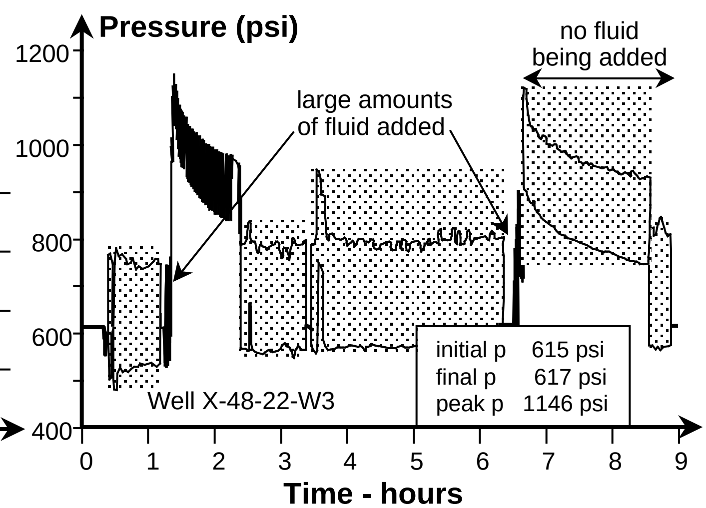

Fig 5: P-response curve, Well X-48-22-W3

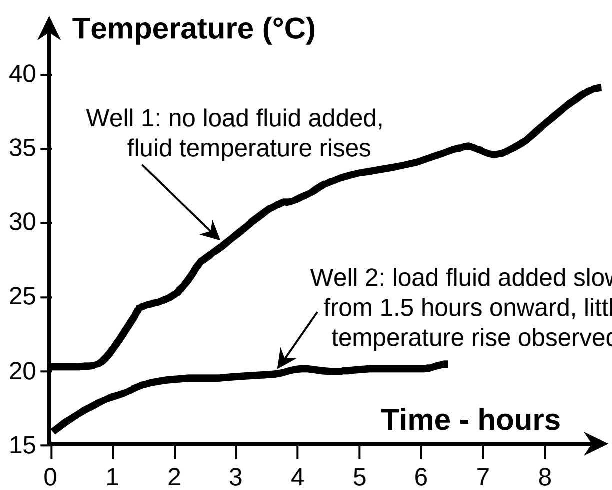

Fig 3: Temperature changes from frictional losses

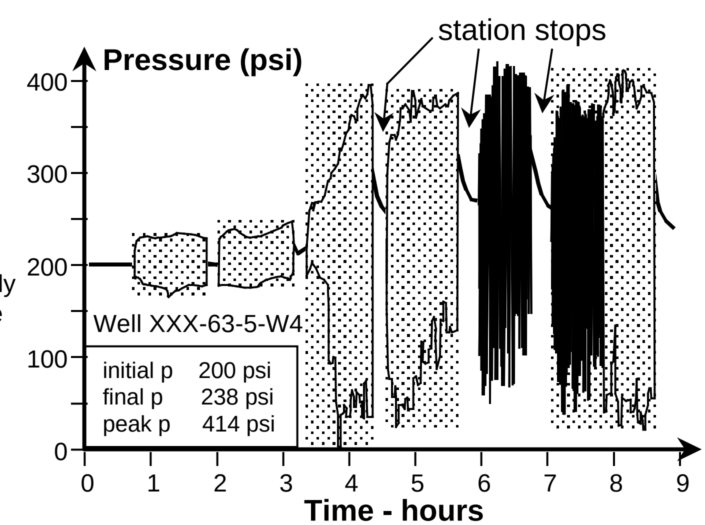

Fig 6: P-response curve, Well X-63-5-W4

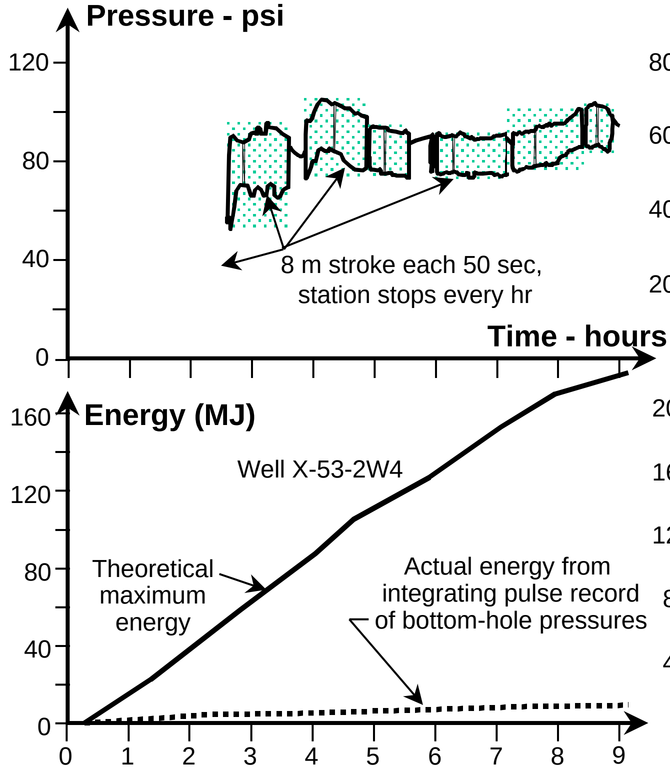

Fig 7: Energy efficiency for a poor case

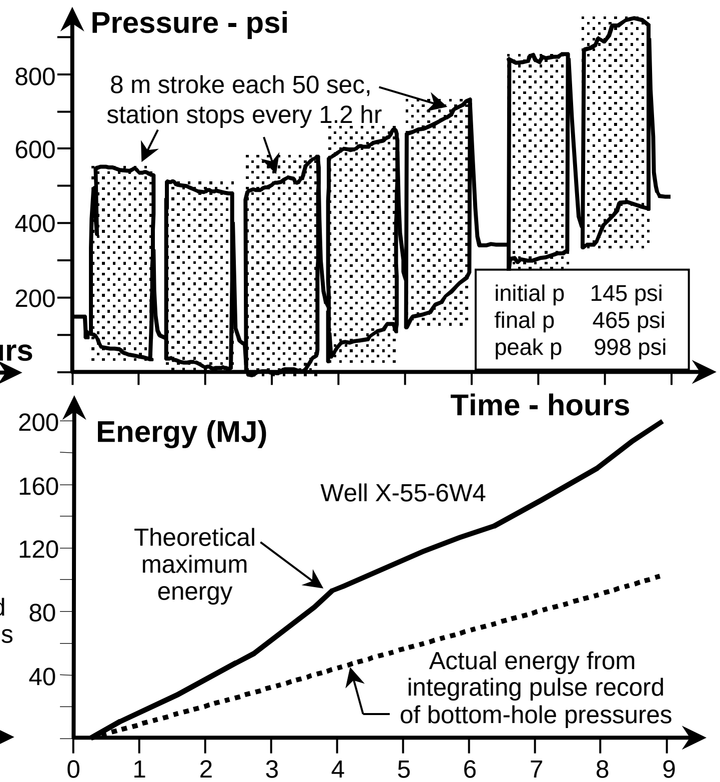

Fig 8: Energy efficiency for a good case