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Adopting Aphron Fluid Technology for Completion and Workover Applications

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Abstract

The literature describes several applications where Aphron fluid technology has been applied in both drilling and re-entry scenarios and includes an extensive description of how this fluid system works. A highly efficient leak-off prevention mechanism makes aphron based fluid systems beneficial for certain completion and workover applications as well, where formation damage could be avoided by the practical elimination of fluid-fluid or fluid-rock interaction or where simply the workover objectives can be achieved by obtaining efficient circulation of fluid to surface. Completion and workover applications for this fluid system have not been extensively reported.

This paper reviews three applications of Aphron fluid technology in different completion and workover scenarios. The selected cases were reviewed to present some of the technical and operational lessons learned and to some extent discuss the observed formation cleanup behavior. The following three applications were reviewed: completion of a dual string sour gas well, using an oil based aphron system for kill fluid, with practically no kill fluid loss to a hydraulically fractured formation; the completion of additional zones within a depleted dolomitic limestone formation on two wells where the method of Aphron fluid placement was found to significantly affect fluid losses; and finally, the enabling of the provision of annular pressure support at pressures which approached the hydraulic fracture opening pressure of a shallow zone while hydraulically fracturing a deeper zone through tubing with a packer.

Introduction

The mechanisms by which the Aphron fluid system operates make it a reliable tool for certain completion and workover applications. These mechanisms have been described extensively in the literature (Brookey 1998; Ivan et al 2001; Growcock et al. 2005a; Catalin et al. 2002; Hoff, O'Connor and Growcock 2005). Moreover, the presentation of field performance data for Aphron fluids in drilling and re-entry operations is also extensively published (Ivan et al. 2001; White et al. 2003; Brookey et al. 2003; Rea et al. 2003 and Kinchen et al. 2001). Lessons learned from the performance of Aphron fluids in a wide range of applications have caused a specific profile to evolve for the effective use of this fluid technology. Brookey (1998) showed that the high low shear rate viscosity (HLSRV) of the Aphron fluid system, which provides the proper environment for aphron bubble formation and survival, also provides a high resistance to flow under low shear conditions, which significantly inhibits initial fluid loss to the formation. Brookey (1998), supported by Ramirez et al. (2002) showed that the creation of aphron aggregates is an effective filtrate control mechanism which further reduces fluid loss. Formation damage prevention is attributed to the inert gas which makes up the majority of an aphron aggregate, combined with the limited amount of fluid invasion into a potential leakoff zone. Adverse fluid-fluid and fluid-rock reactions are prevented because the completion and workover fluid is not available as a reactant or contaminant.

The sealing mechanism is controlled by differences in fluid and formation pneumatics and hydraulics (Catalin et al. 2002). When wellbore pressures exceed formation pressures, aphrons will migrate with the pressure gradient from the wellbore to the formation. Growcock et al. (2005a) observed that aphron bubbles will move to the leading edge of a differential pressure driven migrating fluid front. The aphron bubbles will individually bridge in pore throats and will agglomerate to bridge larger apertures inside the formation. Sealing is achieved quickly and to the extent necessary to establish a balance between the formation and wellbore pressures. The seal remains intact and stable until fluid properties or wellbore hydraulics no longer support individual aphron or aggregate aphron seal integrity. If fluid LSRV is lowered to below about 40,000 cP the aphrons become unstable and begin to break apart. If wellbore pressure is lowered to below the formation pressure the aphrons will again move with the gradient, from the formation into the wellbore.

The unique properties of Aphron fluids have produced growing interest for their use in certain completion and workover applications. The authors reviewed several projects in western Canada and have presented three cases which illustrate some of the benefits and challenges of using Aphron fluids in completion and workover applications.

Case Studies:

Case 1

In this case, significant and relatively complex dual string snubbing operations were avoided. This well, shown in **Fig. 1**, was to be dually completed for sour gas production in two Upper Cretaceous sandstone intervals in the north central foothills region of Alberta. After hydraulic fracturing and initial cleanup flow operations, an oil based Aphron completion and workover fluid was used to kill the upper formation in order to enable the well completion to be finished using standard well servicing equipment. After eight days of service rig operations which included multiple tubing trips, an aggressive proppant cleanout using a mud motor, mechanical bridge plug retrieval and the installation of dual production tubing strings, the full original kill fluid volume was recovered. Nitrogen circulation through the completion tubing was used to expedite fluid recovery and the upper interval immediately flowed at a rate indicative of an effective stimulation. **Fig. 2** shows the shallow interval gas production rate throughout the completion and cleanup flow operations and **Fig. 3** shows the corresponding fluid loading throughout the completion operation.

Fluid properties were not perceived to be optimal for this well servicing application as the fluid was purchased from another operator who had used it as a drilling fluid in a multiple well program. Despite an abnormally high LSRV and the presence of drilling fines gained during its previous drilling service, this recycled fluid proved to be suitable for this application and did not damage the well.

Case 2

This well and the next were completed in a Mississippian aged dolomitic limestone gas reservoir having a gross pay thickness of 90 m, estimated reservoir pressure of 6 MPa and a vertical depth to the pay zone top of 1446 m. Both wells were the subject of workovers to increase gas production by completing additional pay sequences which were located amongst the existing completion intervals.

With the depleted reservoir pressure in this field, well servicing operations when conducted using produced water as a kill fluid, have historically incurred continuous losses of 6-8 m^3/hr, with a few hundred cubic meters of kill fluid loss over the course of a workover operation having been common. High fluid loss volumes would often lead to poor well performance during the early post workover production period, and in some cases well performance would suffer for a period of several months. In recent years snubbing has evolved as the preferred method for well intervention because fluid loss volumes could be significantly reduced.

Case 2a

The first workover was proposed to complete two additional pay intervals. Acid and hydraulic fracturing operations were performed respectively on the two new intervals. **Fig. 4** shows the wellbore configuration during and after the workover. The well was killed with a full column of Aphron workover fluid before retrieving the original completion equipment and then perforating and acidizing the deeper interval. The Aphron fluid was circulated out of the tubing and then the tubing was swabbed dry before conducting an acid squeeze. A brief evaluation after the acid job showed poor inflow and then after recovery of the spent acid the zone was re-killed with Aphron workover fluid before being isolated below a bridge plug. Operations continued with the second, shallower interval, which was isolated to conduct a hydraulic fracture using the previously set bridge plug and a service packer. A surface pressure of 3 MPa was applied on top of a full annular column of Aphron workover fluid without inducing losses and the shallower zone was hydraulically fractured, placing only 30% of the planned proppant tonnage in the formation before a premature screenout. Poor inflow was also observed from this zone and it was left loaded with a high volume of stimulation fluid. To this point no observable Aphron fluid volume had been lost to the reservoir.

Operational problems were encountered during oil tool setting, which were attributed to perforating debris and possibly other solids suspended in the fluid column. In an attempt to exploit the stable aphron seal within the formation, on day 17 as shown on **Fig. 5** it was elected to circulate the well to produced water for the remaining well servicing procedures. The Aphron workover fluid was recovered from the well by circulation with produced water and then the packer was unset but lost during recovery from the well. While fishing, and after a day of well servicing operations, the Aphron seal degraded sufficiently to permit significant enough fluid leak off to cause a substantial loss of the fluid column. A kick occurred during packer recovery and continued gas influx was contained with a produced water kill fluid column. In a failed attempt to stabilize the kill fluid column, a low volume Aphron pill was squeezed through the tubing from an intermediate depth in the well. An effective and stable kill fluid column was not regained, and the remaining operations were executed with significant additional produced water kill fluid loss. **Fig. 6** shows well performance both before and after this workover. Though a production success could not be claimed, significant observations were made which will affect ongoing operations with this fluid. The observations are:

- The affect of entrained air on the surface volume of Aphron based completion and workover fluids must be recognized during kill fluid placement and recovery, ensuring that sufficient fluid of an understood weight is placed in the well. Growcock et al. (2005b) observed a mud weight gradient which reflected Aphron compressibility in the well.

- Wireline tools, including a wireline set bridge plug were deployed without incident.
- A packer setting failure occurred after running a mechanical set service packer through a newly perforated interval. Examination of the failed packer indicated that the fluid bypass area was plugged with perforating debris. It appears that the high LSRV enabled solids in the static fluid column to remain suspended until they were filtered out in the packer bypass flow area. The surface fluid handling process was subsequently improved by adding solids removal equipment.
- Upon recovery, after several days in the well without circulation, the workover fluid rheology properties were stable and Aphron content was consistent with the originally placed fluid. An upper time limit to Aphron stability under static downhole conditions has yet to be defined.
- For this case it is likely that the stability of the aphron seal inside of the formation was reduced when surge and swab pressures incurred during fishing and pipe movement contributed to its degradation. With Aphron fluid inside the wellbore, it is likely that the aphrons would have remained intact and the seal would have regenerated each time it was destabilized with no significant fluid loss, however with produced water inside of the wellbore the aphron seal quickly broke down under surge and swab conditions.
- The method of fluid placement is a vital factor in the success of placing a stable aphron seal. The failed attempt to place an Aphron fluid pill was made with the tubing bottom 350 m above the top of the pay zone. In this case the Aphron rheological properties would have broken down as dilution occurred into the produced water wellbore fluid. The Aphron pill and a substantial produced water volume were lost to the formation while recovering the packer and bridge plug and installing the production tubing.

The aphron seal, once stabilized, is maintained or strengthened by the addition of further aphron bubbles. Conditions for seal maintenance would be enhanced by the continuous circulation of fresh Aphron fluid inside the wellbore adjacent to the seal. Reduced seal stability would be expected with static Aphron fluid in the well at the invasion zone, though this condition was adequate to maintain a long term seal in this case. The lowest seal stability would be expected when a non Aphron fluid was present in the well, especially under unstable, surging bottom hole pressure conditions, as occurred in the later stages of this operation. The next case outlines a similar workover application in the same reservoir which was successful.

Case 2b

This well was the subject of a workover to add a new, deeper completion, as shown in **Fig. 7**. Before recovering the original production tubing string, the well was killed by balancing a column of recycled Aphron workover fluid in the bottom half of the well, with a fresh water column to surface. Produced water was left across the proposed new interval and the well was perforated with wireline conveyed casing guns. A packer was run on tubing without incident and the tubing was displaced to fresh water, pushing the Aphron volume fully into the annulus before setting the packer between the intervals. A surface pressure of 6 MPa was maintained on the annulus while pumping the fracture stimulation. **Table 1** shows the Aphron injection volumes, as measured at surface**.**

TABLE 1–APHRON INJECTION VOLUME, MEASURED AT SURFACE, CONSTANT APPLIED PRESSURE

Observation Time	Observation	Volume (m^3)
day prior to fracture stimulation	short duration injection with initial high rate loss	0.7
during fracture stimulation	initial high rate loss	1.0
during fracture stimulation	low rate loss	0.4

Fluid losses for the complete workover are summarized in **Fig. 8**. All but 0.5 m^3 of the Aphron fluid was recovered by circulation after installation of the completion equipment. Post workover production results, **Fig. 9**, show that the well is producing at a higher gas flow rate, and further analysis has suggested that additional reserves are being drained.

Case 3

This case describes two wells in the Cretaceous conglomerate sands of the Deep Basin region in Alberta, where Aphron workover fluid was used to provide a means of preventing fluid leakoff under high differential pressures, so that a high casing pressure could be maintained during fracturing operations conducted through the tubing. In order to accommodate expected high fracture treating pressures, the tubing maximum pressure capacity was increased above its derated internal yield pressure by maintaining a high annulus pressure during the treatment.

Case 3a

For the first well, a retrievable casing patch type packer was proposed to protect the shallower of two completion intervals from high annulus pressures which were desired during a fracture treatment of a deeper completion interval. However, operational problems were encountered during two attempts to install the tool. As a substitute for the casing patch, an Aphron fluid system was circulated into the annulus. The casing pressure was maintained near the previously observed fracture closure pressure of the shallower interval throughout the fracture treatment. **Fig. 10** shows the well configuration during this operation.

Overall fluid losses during the workover are described in **Fig. 11**. The shallower sand, which was hydraulically fractured during the original well completion, now acted as a sink, and caused ongoing workover fluid losses to occur until the well was circulated to the Aphron fluid system. Two observations are notable with this application. Firstly, ongoing fluid losses into a hydraulically fractured and depleted completion interval were arrested once Aphron fluid was circulated across the interval. Furthermore, an aphron seal was maintained at pressures approaching the originally observed hydraulic fracture closure pressure.

Case 3b

This case is similar to the previous well. The casing was filled with Aphron workover fluid and the surface annulus pressure above a packer, with an exposed hydraulically fractured completion interval, was held at a sufficient level to enable the anticipated tubing pressure to be achieved during the fracture treatment of a deeper sand. Aphron fluid injection volumes into the upper completion interval, before and during the fracture treatment are noted in **Table 2**.

TABLE 2–ANNULUS PRESSURE SUPPORT OBSERVATIONS

Observation Time	Observation	Surface Annulus Pressure (MPa)	Injection Volume (m^3)	Average Injection Rate (m^3/min)
one day prior to fracture	19 min duration, constant injection rate	25	2.6	0.14
during hydraulic fracture	3 hr duration, high rate followed by slow pressure bleed off	21	3.4	0.02

The full annulus volume was 17 m^3 and the noted injection volumes were measured at surface. The surface annulus pressure and injection volume data suggest that the upper completion interval was effectively sealed at a surface pressure of 21 MPa, which approaches the previously observed hydraulic fracture opening pressure for that interval. On the original fracture treatment for this zone, a bottom hole closure pressure of 47 MPa was measured. For this workover, with an Aphron pressurized density of 1035 kg/m^3 and with the shallow completion interval depth of 2883 m, these observations suggest that the hydraulically fractured shallow interval was effectively sealed with Aphron fluid at the full previously observed fracturing pressure. **Fig. 12** shows a plot of this data along with the closure pressure which was measured during the original hydraulic fracture of the shallow interval.

Both wells in this case experienced a productivity improvement under comingled flow conditions however as of publication, isolated testing had not been done of the shallower intervals which were exposed to Aphron workover fluid under a high differential pressure.

Discussion

Seal Placement and Maintenance

Through investigating early cases where Aphron fluids were used in completion and workover scenarios, several lessons were learned about how to appropriately apply these fluids in a well servicing environment. The conveyance method for delivering aphrons to an open formation appears to be an important factor in achieving effective seal stability. White et al. (2003), Brookey et al. (2003); Rea et al. (2003) and Kinchen et al. (2001) described drilling experience which found that circulating Aphron fluid across a producing zone can provide an excellent seal with low fluid loss. This is consistent with observations made in the present cases, where additionally it was observed that bullheading or squeezing a static column of Aphron fluid will yield various amounts of fluid loss. Aphron microbubbles range in size from 10 to 100 μm, therefore the gross number of aphrons required to form a seal across a previously perforated and hydraulically fractured formation is likely to be large. The number of aphrons that can be supplied to such zones is limited by, among other factors, the volume of Aphron fluid exposed to the zone, which will be far greater with a circulating column than with a static column. The HLSRV property of an Aphron fluid will cause it to exhibit a viscous resistance to flow not seen with produced water or other kill fluids. Nevertheless, any attempt to place an aphron seal with a static fluid column should be avoided whenever possible, since Aphron fluid with HLSRV imbedded in formations may pose a challenge to effective well cleanup. When an adequate seal was established by circulating Aphron fluids across a producing zone, allowing the fluid column to go static did not result in seal degradation or whole Aphron fluid loss. In the present case, where the aphron seal was established under circulating conditions, stability was maintained for up to eight days without incurring fluid losses. Though the life span for an aphron seal stabilized in a static Aphron fluid column has not been established, lab based observations by Growcock (2005b) of aphron bubble longevity would suggest that there is a time limit.

An effective aphron seal was observed at pressures which approached the previously observed hydraulic fracture opening pressure, demonstrating that the leakoff prevention mechanisms work, even at very high differential pressures. A stable injection rate was achieved on one of the cases, indicating that some caution is needed under the application of high bottom

hole pressures, exceeding the fracture opening pressure. For an Aphron column applied to a previously fractured formation, even with an effective seal, under high squeeze pressures, reinitiation of hydraulic fracturing will become a risk.
Growcock (2005b) reported that aphron microbubbles formed in a HLSRV fluid, withstood pressures up to 28 MPa without collapse. Unpublished field data provides evidence that the upper limit threshold for aphron survivability under elevated pressures may be even higher than this. The present cases suggest that an effective seal was maintained at bottomhole pressures exceeding 42 MPa. This survivability may be due to the pressure gradient which exists across an aphron seal, with formation pressure on the low pressure side and the high pressure existing only on the wellbore side. A model describing aphron survivability in the conditions which are present across a formation seal, at pressures above the laboratory investigated limits is presently not defined in the literature.

Fluid Compressibility

Fluid column considerations must include the density and volume variance which results from the compressible nature of these fluids. Although aphrons can endure in a high pressure environment, with a gas filled core, aphron bubble diameters predictably will reduce with increasing pressure. Consequently, the overall Aphron fluid system is compressible, and at hydrostatic pressure conditions representative of most wells, will reduce in volume by a value which asymptotically approaches the surface entrained air total volume.

Field Operations

Aphron fluids recovered from both drilling and completion operations have been stored, transferred and successfully reapplied in other completion and workover projects. Despite the presence of drilled solids, produced fluids, mill cuttings and other contaminants, recycled Aphron fluids still provided efficient sealing performance. This is attributed to the highly effective suspending capacity of the fluid phase of the Aphron system and the fact that the aphron microbubbles move ahead of the HLSRV fluid front to prevent sustained fluid invasion. Fluid borne contaminants are simply not available to producing formations and therefore present no significant risk of formation damage.

The initial costs and high fluid recoverability involved with Aphron fluids in completion and workover operations provides motivation for the implemention of a coordinated full cycle approach to Aphron fluid management. A cost effective method for adapting Aphron fluids to completion and workover applications is to incorporate a system of fluid management which facilitates recovery, storage and reuse. Components of such a system might include the following:

- Reduce–Low fluid loss rates in well servicing operations provide a high degree of predictability for fluid requirements and recovery volumes. New volumes can be built with close tolerances, reducing excess volume normally associated with contingency.
- Reuse–Wells are circulated out with either pressured nitrogen, brine or frac oil to efficiently recover the Aphron fluids. The Aphron fluid may then be stored or transferred to another location.
- Recycle–In field observations Aphron fluid integrity was similar before and after the well servicing operations. Storage of these fluids requires periodic agitation and treatment for the prevention of microbiols. Fluid reconditioning may be required in some cases.

Systems which have been designed to ease the handling of invert fluid systems have proven to be useful in the loss prevention of Aphron fluids while handling pipe at the rig floor. The small volumes of Aphron fluids that either inter-mix with displacement fluids or remain as residue on rig equipment have been disposed of according to the applicable regulations for fluids from producing wells.

Active solids management is traditionally not a concern with the clear, filtered brines that are normally deployed in well servicing operations. The rheological properties which help prevent fluid invasion with Aphron based systems also enable solids suspension in the fluid column, which could interfere with oil tool deployment and retrieval. Solids removal can be addressed on the surface for the entire fluid system with the various types of traditional drilling solids removal equipment and in the wellbore, for specific contaminants like perforating debris, with the various brands of in-well filtering tools.

Conclusions

1. Aphron fluid technology was applied successfully in several completion and workover applications to prevent wellbore fluid loss, enabling well operations to be carried out under dead well, static fluid conditions. This has simplified some well servicing operations, and enabled some complex operations to be executed with reduced risk, for example by eliminating the need to snub in certain cases.
2. The compressible nature of the Aphron fluid system requires recognition when installing and removing fluids from the well and also when applying a squeeze pressure on top of an Aphron column. Furthermore, migration of the stabilized aphron bubbles through these fluids when exposed to a pressure gradient, such as across a formation seal, can be expected to lead to an apparent bulk fluid loss under static fluid conditions, with a resultant surface pressure reduction, when the actual mechanism is the loss of aphron bubbles from the bulk fluid to the aphron bubble front at the seal.
3. The method to achieve an effective and durable formation internal seal must respect the unique properties of Aphron fluids. For well servicing applications it may be helpful to view the sealing mechanism from two standpoints. Firstly, effective seal establishment is enhanced by Aphron fluid circulation inside of the wellbore, with the seal effectiveness largely being determined by the adequate supply of sufficient aphron bubbles to produce a substantial seal thickness. Secondly, seal longevity requires some degree of maintenance, with a positive balance being

required between those factors which either enhance or degrade the aphron seal.

4. The observation of an effective aphron seal at bottom hole pressures which approach the known formation fracturing pressure warrants further investigation to describe seal behaviour under high static pressures and the interaction between the aphron seal, the pre-existing hydraulic fracture and the near wellbore stress state.
5. Other potential completion and workover applications for Aphron fluids may exist, such as the enabling of efficient fluid circulation in the presence of exposed depleted pressure reservoirs. Unreported experience suggests that Aphron fluids may be useful for increasing the likelihood of obtaining efficient circulation in primary and certain remedial cement applications. Employing a modified version of these fluids to enhance certain well stimulation programs may be possible; and lastly, innovative operational practices such as pressurized forced air formation of aphrons could permit use of an enhanced version these fluids to improve seal formation, even in very high leak off situations.

Acknowledgements

The authors would like to thank Devon Canada Corporation, operator of the wells in these case studies, for permission to publish the information from which these conclusions were drawn and furthermore wish to encourage and invite both the publication of other applications of this technology and a more rigorous examination of the various Aphron fluid behaviors observed in these cases.

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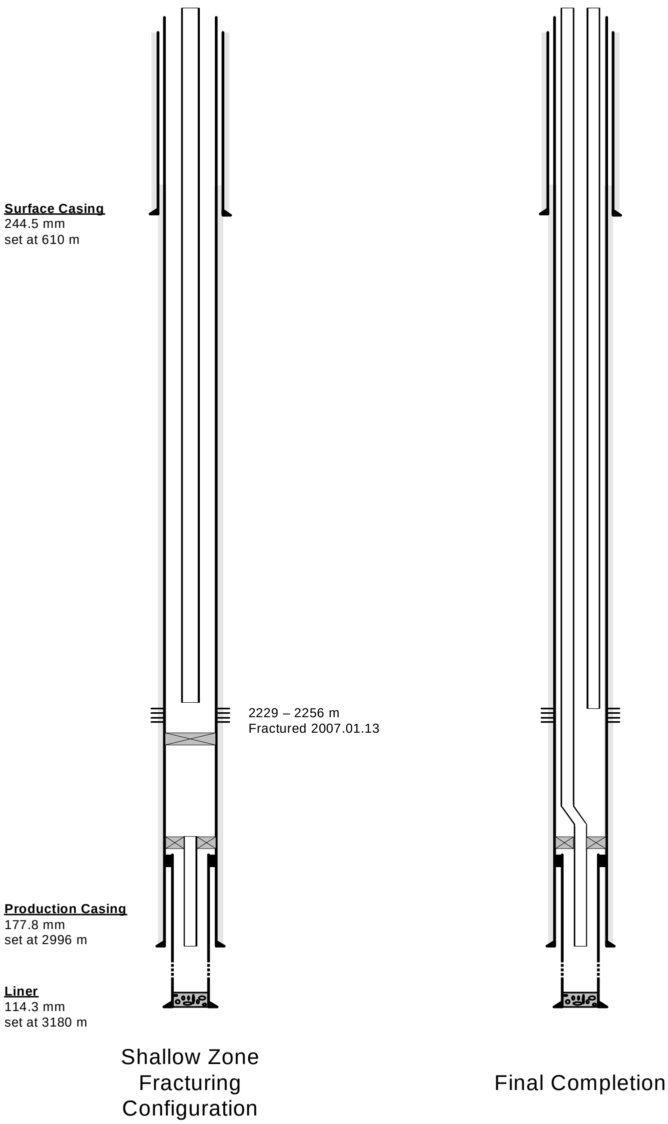

Fig. 1–Case 1: the shallow completion interval was killed using an oil based version of Aphron fluid technology in order to install a dead leg tubing string for hydraulic fracturing and then to configure well for dual string production.

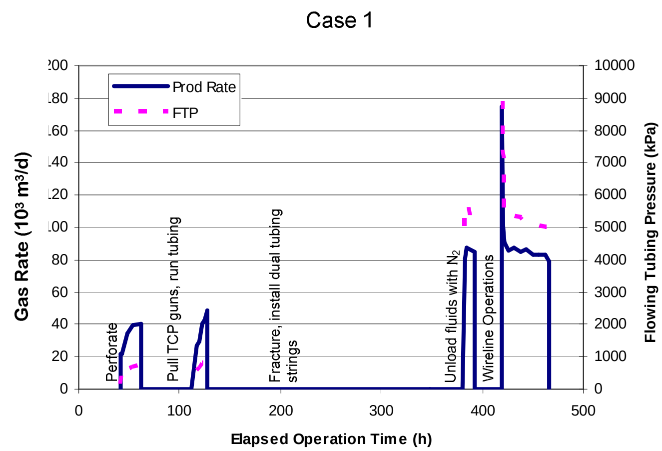

Fig. 2–Gas production rates observed during the completion operations.

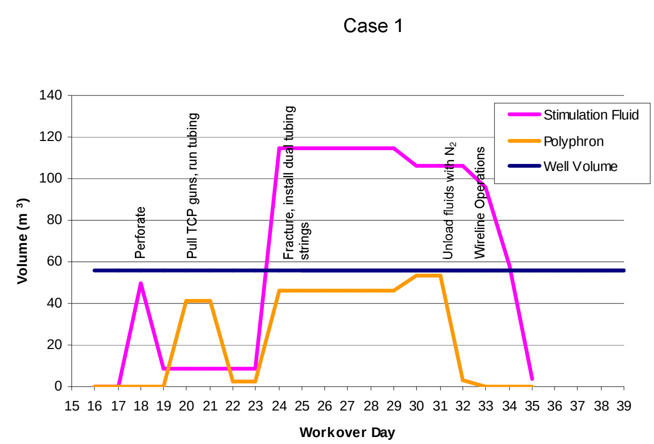

Fig. 3–Fluid losses are presented by fluid type with the major phases of the completion operation noted.

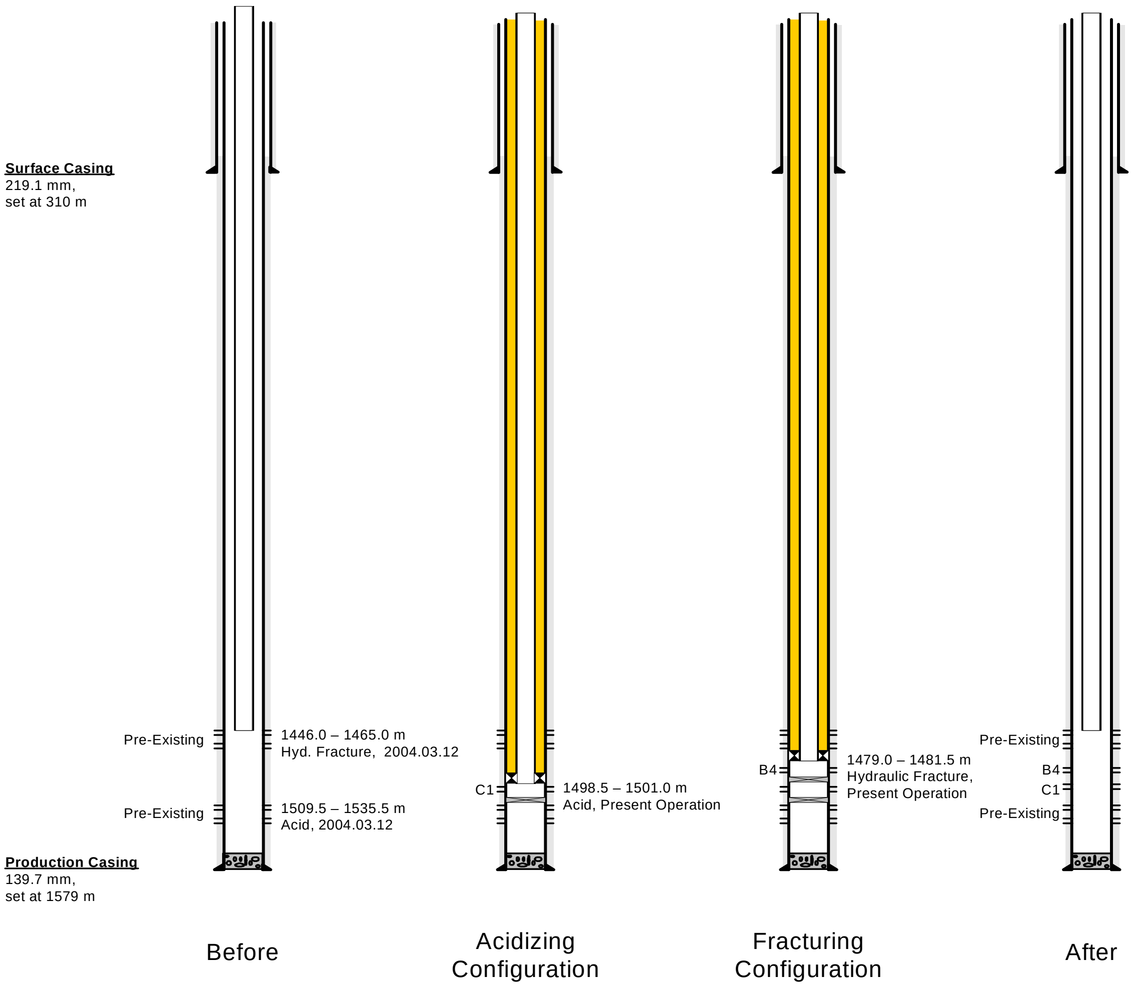

Fig. 4–Case 2a: two zones were added, acidized and hydraulically fractured within the existing completion intervals.

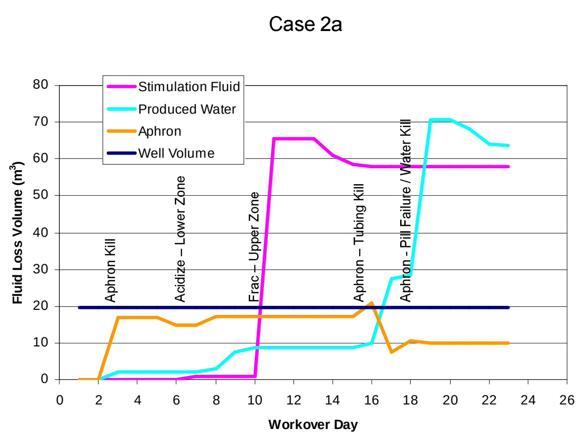

Fig. 5–Fluid losses are noted for each fluid type during the workover operations.

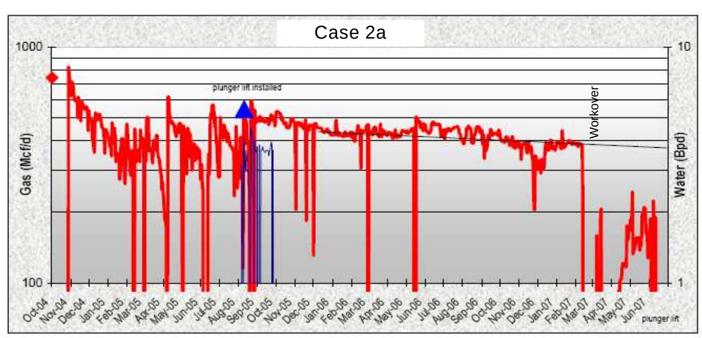

Fig. 6–Well production pre- and post-workover.

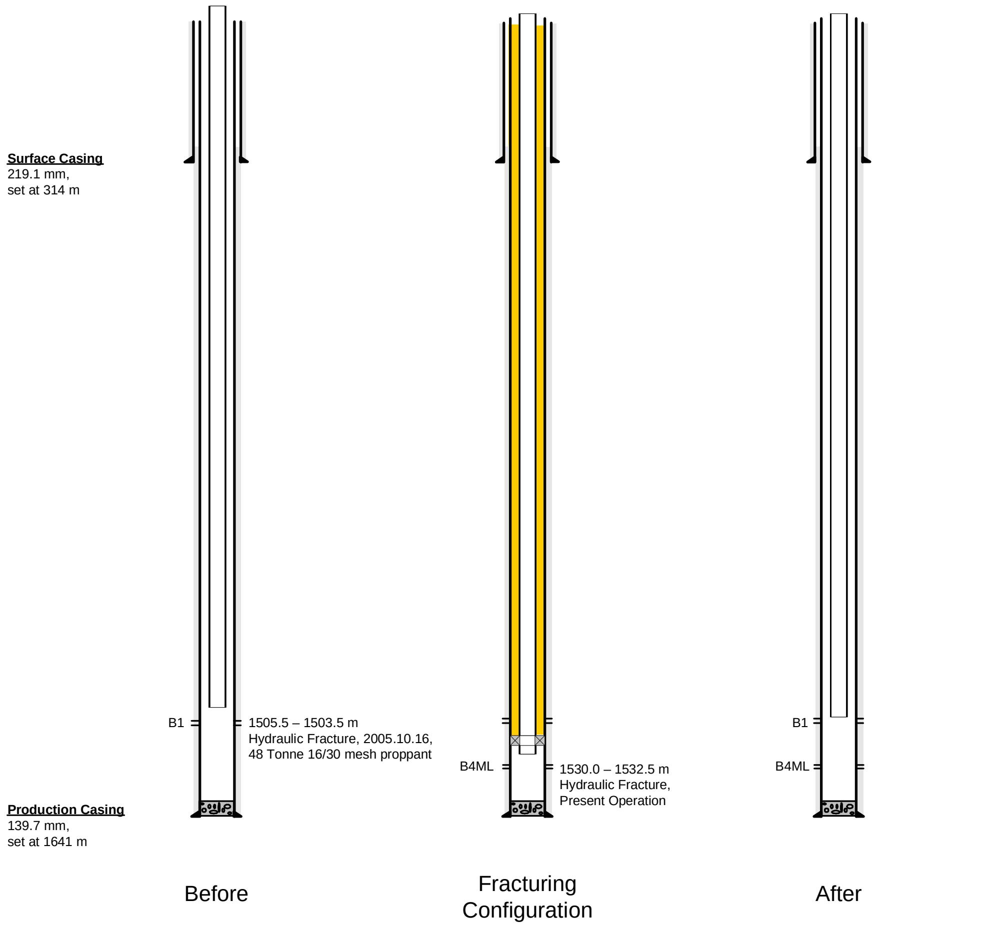

Fig. 7–Case 2b: a single zone was added and hydraulically fractured below an existing completion.

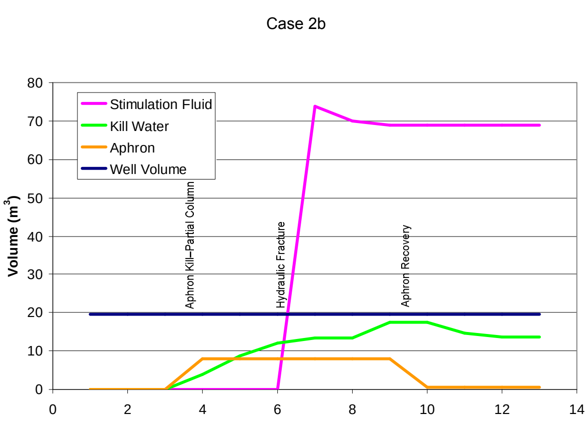

Fig. 8–Fluid losses are noted by fluid type during the workover operations. A partial column of Aphron workover fluid was used to kill the well. All Aphron fluid was recovered from the well during this operation.

Fig. 9–Well production pre- and post-workover.

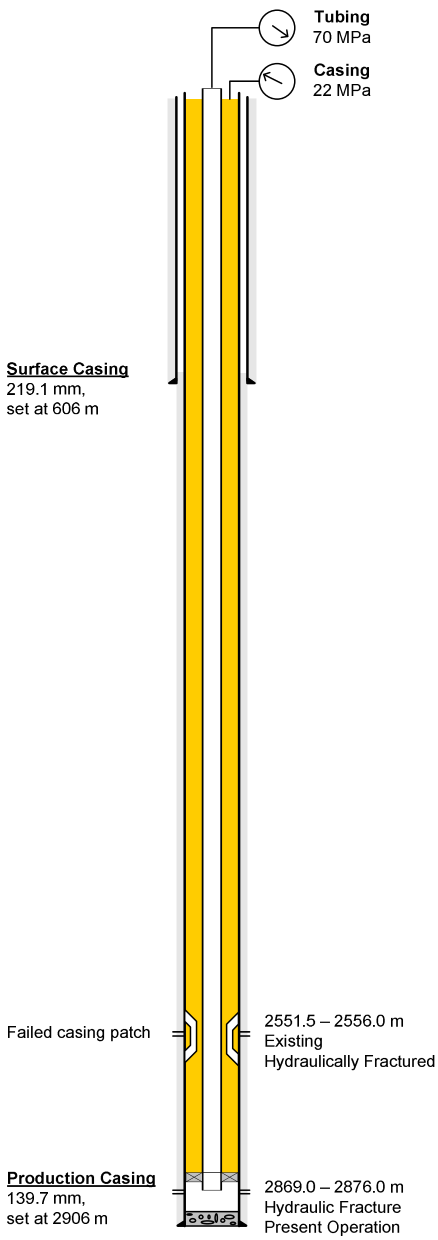

Fig. 10–Case 3a: a single zone was perforated and fractured below an existing hydraulically fractured completion interval. Aphron workover fluid was used to support a high annulus pressure after a temporary casing patch twice failed to set across the shallower interval.

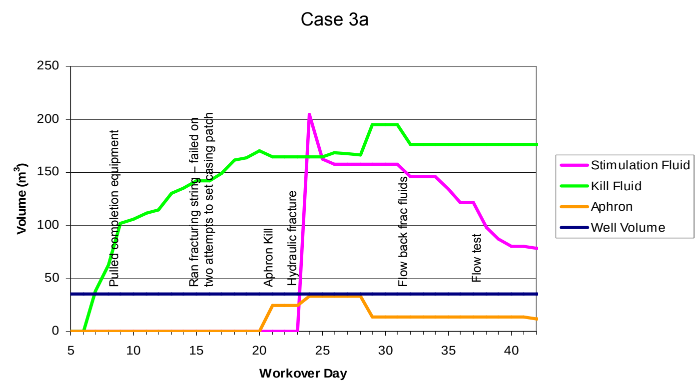

Fig. 11–Workover fluid losses are shown for each fluid type. High losses were incurred until the well was circulated over to an Aphron workover fluid on day 20.

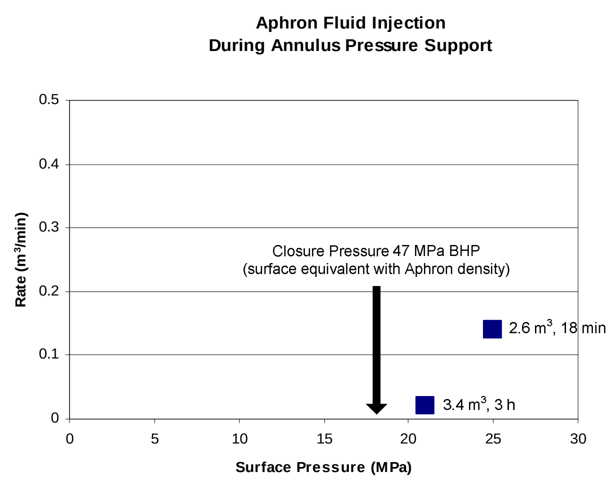

Fig. 12–Case 3b: annulus injection pressure observations suggest that the Aphron fluid provided an effective seal, even above the previously observed fracturing pressure of the upper interval. Injection volumes and durations are noted.