Crushing of Tubing within Horizontal Casing

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Tubing Crushing Modelling – Boneyard Test Facility, Peach Valley, Delta Colorado July 2013
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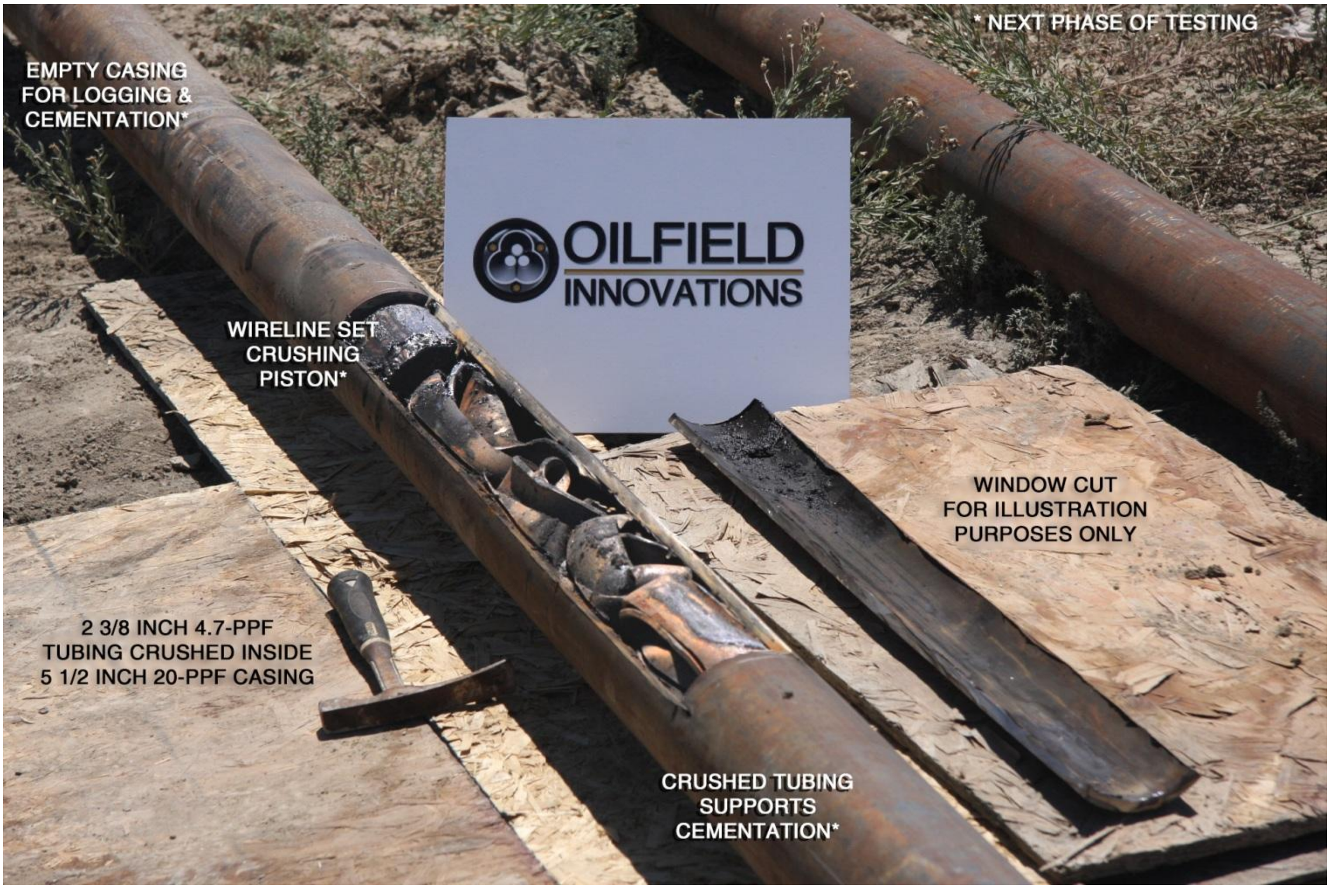

Figure 1 – Modelling Run [5] Crushed 2 3/8” Tubing viewed through a window cut in 5 ½” casing.

Abstract

Horizontal physical modelling of the compaction of 2 3/8” 4.7 pound per foot tubing within 5 ½” 20 pound per foot casing yielded a 46% compression ratio within three (3) separate tests, wherein the tubing occupied 54% of its original axial length after it was crushed within the horizontally placed casing. A number of nuisances regarding tubing crushing were discovered. Point loading of the crushing piston and friction within a horizontal bore were found to be significant factors. Modelling also indicated that the displacement rate of the pump used was important as additional fluid displacement can compensate for minor leakage about the piston. In summary, six (6) model runs provided sufficient information for planning of vertical modelling and well testing of Oilfield Innovations’ patented process to achieve rig equivalent wireline and/or slickline well abandonment, whereby the crushing of tubing within casing can provide space for logging casing cementation and provide a rig–equivalent unobstructed cement abandonment plug.

Purpose of Modelling

The results of Oilfield Innovations Limited’s (OILtd) July 2013 physical modelling of 2 3/8 inch 4.7 pounds per foot (ppf) OCTG tubing crushing within 5 ½ inch 20-ppf OCTG casing confirmed that OILtd’s patented and patent pending innovations are viable.

Initial physical horizontal modelling of the crushing process will be used for planning subsequent vertical modelling and actual well abandonment both onshore and offshore.

Modelling also verified that Oilfield Innovations’ onshore and offshore rig-equivalent rig-less well abandonment technology is viable for meeting U.S. Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE)[1] requirements, the Texas Railroad Commission requirements[2], Oil and Gas UK 2012 Well Abandonment Guidelines[3], and NORSOK revision 4 well integrity standards[4].

The modelled tubing weakening scenarios and associated tubing compression results simulated a number of the proposed approaches to well abandonment that can be used to meet the various regulatory requirements and guidelines; whereby an unobstructed space can be provided for logging primary casing cementation and placing a rig equivalent unobstructed cement plug using the rig-less scenarios described herein.

Additionally, the use of minimalistic facilities and equipment demonstrates the efficacy of this innovative well abandonment approach in remote locations and that the overall cost of well abandonment can be lowered by using minimal resources to provide a geologic time frame well barrier element according to applicable regulations and industry best practices.

Summary of Results

Modelling the crushing of tubing within a horizontal casing proved the core principles and viability of OILtd's Rig Equivalent Wireline Well Abandonment Patents because the 46% compression ratio was achieved within a worst case scenario where friction is at its highest levels.

Various tubing lengths and tubing weakening scenarios were simulated during horizontal physical modelling runs to provide frictional data for further vertical modelling and subsequent well plugging.

Worst case results during testing of the horizontally orientated casing for physical modelling showed that a 46% compression ratio could be expected for crushing of 2 3/8 inch 4.7-ppf tubing within 5 ½ inch 20-ppf, wherein the tubing occupied approximately 54% of its original axial space after crushing.

The physical simulations that resulted in 46% compression ratios comprised:

i) two simulations that crushed a single weakened tubing joint within dry horizontal casing, and

ii) a simulation that crushed three (3) joints, comprising two (2) weakened and one (1) unweakened tubing joint within dry horizontal casing.

During crushing simulations various modelling difficulties stemmed from the use of minimalistic hardware store equipment and short or weak pistons, which resulted in a number of failed model runs.

Test Facilities, Equipment & Rig-up

Figure 2 – Boneyard Test Facility

Physical modelling occurred within the yard shown in Figure 2, locally known as the "Boneyard," which is located adjacent to the pictured grain field in Peach Valley near the town of Delta Colorado.

Despite the Boneyard's lack of utilities and the absence of oilfield equipment, the patented crushing process worked and, thus, showed that minimalistic equipment and facilities can be used for remote location and minimum facility well abandonment.

As shown in Figures 3 to 5, water was injected into the casing using minimalistic pumps that drove a crushing piston, which crushed tubing within a dry casing used to monitor any leakage past the piston.

Figure 3 – Pressurized Wet Piston End

The Figure 4 common garden variety and well-worn gasoline driven water jetting pump was used for modelling runs [1], [3] and [6]. Similar pumps are commonly available at almost any hardware store for an insignificant price relative to oilfield equipment.

Figure 4 – Common gasoline driven Water Jetting Pump

The water jet pump of Figure 4 provided approximately four (4) gallons per minute at pressures less than one hundred (100) pounds per square inch (psi). As pressure increased the flow rate decreased and the gasoline engine stalled; the pump was unable to achieve pressures above 3,000-psi. A second, slightly newer, water jet pump with a stronger motor was used on model run [2] to achieve 4,000-psi, but the stronger motor, which did not stall, effectively destroyed the pump.

Figure 5 – Low Volume 10k Pneumatic Test Pump

The Figure 5 pneumatic test pump was used to achieve higher pressures for modelling runs [4] and [5], although the volume displacement over time was less than ¼ gallon per minute during pumping.

Accordingly, model runs [1] to [6] suffered from an inability to displace significant volumes at higher pressures, which prevented continuous crushing. Continuous crushing could have been achieved using oilfield specification pumps that can displace significant volumes at high pressures.

Figure 6 – Ejecting Crushed Tubing Model Run [6]

After using the minimalistic equipment to its full extent, the casing end-cap was removed from the “dry” end of the casing in simulations [1] to [4] and [6], and the crushed tubing was pumped out until the pistons exited and the water on the wet end of the piston was released as shown in Figure 6. After the crushed tubing was ejected it was measured to determine the compression ratio achieved.

For the modelling run [5], shown in Figure 1, a window was cut in the casing to show the crushed tubing in place.

Simulating model runs [1] to [6] in a remote location that lacked normal utilities and used a highly frictional dry horizontal crushing orientation with low volume pump displacement and relatively low pressure capabilities, compared to near vertical fluid filled well bores and high specification equipment achievable within oilfield, demonstrated that Oilfield Innovations patented and patent pending method are applicable to almost any wells including remote location and/or minimal facility installation onshore, offshore and/or subsea oil and gas wells.

Crushing Orientation

OILtd’s July 2013 physical “dry” crush simulations oriented tubing and casing horizontally at ground level as shown in Figures 1, 2 and 6. The dry nature and horizontal orientation of the casing and tubing represents a worst case evaluation of the technology because the orientation and lack of fluid lubrication cause significant tubing-to-casing frictions that are likely to be absent or significantly reduced during vertically oriented downhole crushing.

The simulated dry horizontal compression ratios can be considered conservative compared to a vertical or near vertical “wet” well bore orientation because the “dry” test lacked lubrication and the horizontal orientation moved the point of maximum crushing load to the point of contact between the tubing and crushing piston, which resulted in proportionally increasing “additional” friction as crushing increased that limited the compaction ratio to 46%.

Point of Maximum Crushing Load

The maximum crushing load within a “wet” vertical orientation occurs at a point distant from the crushing piston because fluid lubrication and vertical orientation adds the per linear foot of tubing weight to the crushing load, which induces failure at the lower end of the tubing that supports the piston crushing load and the weight of the tubing above it.

The maximum crushing load within a “dry” horizontal orientation occurs at the crushing piston because the friction associated with splaying, helical buckling, and the weight per linear foot of tubing must be subtracted from the applicable piston crushing load as the distance from the crushing point increases, thus limiting the piston crushing force.

As shown in Figure 7, the normal horizontal frictional forces associated with tubing crushing model runs [1] to [6] involved a friction force ($F_{friction}$) equal to the friction factor (μ) multiplied by the normal force (N). Within a horizontal arrangement, the normal force (N) is equal to the weight of the tubing plus the force induced through helical buckling and splaying resulting from tubing crushing.

Frictional Forces

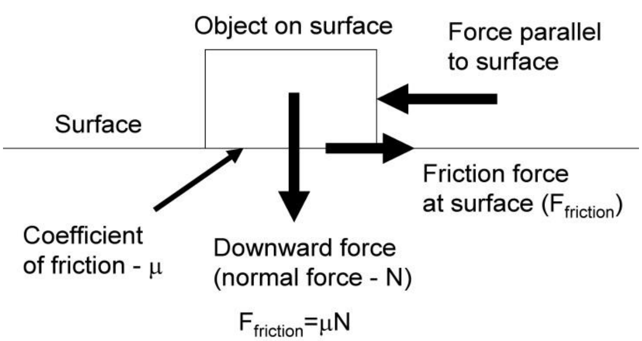

Figure 7 – Horizontal Normal Frictional Force

Without the lubrication of a liquid filled casing, the weight and splaying of horizontally oriented helical buckled and crushed tubing created significant normal force(footnotes 5 to 11) that reduced the piston crushing force and limited tubing compaction ratios to 46%. Horizontal orientation caused the maximum force to be located at the crushing piston by converting the weight of the tubing and crushing forces associated with tubing splaying and helical buckling into frictional forces on the sidewall of the casing that proportionally increased with axial movement and associated tubing deformation, which ultimately caused binding at the crushing piston and limited the crushing ratio.

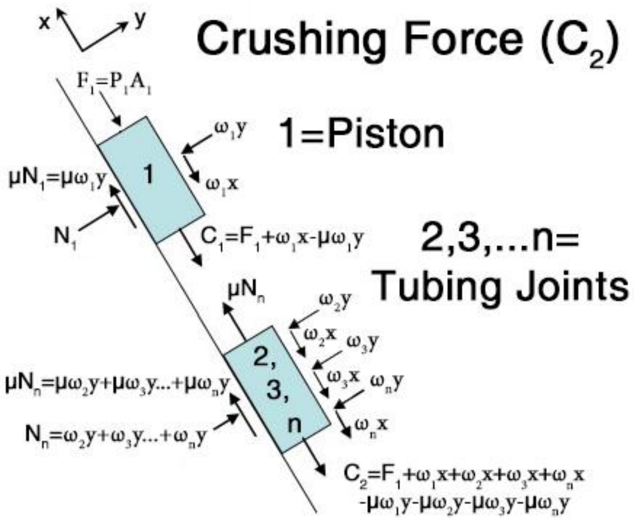

Figure 8 – Near Vertical Tubing Crushing Forces

Figure 8 illustrates that the fluid force (F_1) transferred to the crushing piston is the pressure (P_1) within the casing multiplied by the cross sectional area (A_1) of the piston and casing. Accordingly, the crushing force transferred to the top of the tubing (C_1) is the fluid force (F_1) plus the weight of the piston ($\omega_2 x$) less the friction of the piston ($\mu N_1=\omega_2 y$).

Within an inclined position the piston weight (ω_1) and tubing joint weights (ω_2, ω_3, …ω_n) have axial (x) and perpendicular (y) components associated with the crushing forces (C_1,C_2) and normal force (N_n) that affect tubing compaction, wherein the axial (x) force associated with weight is added to the crushing force and the perpendicular (y) force or Normal force associated with weight, helical buckling and splaying acts with a frictional factor (μ) to resist further tubing crushing.

The frictional force resisting the crushing piston and tubing compaction is equal to the perpendicular (y) component of weight ($\omega_{1\ldots n}$) times the friction factor (μ). The maximum crushing force (C_2) is the crushing force of the piston (C_1) plus the axial (x) component associated with weight that assists and urges the maximum crushing force ($C_2=F_1+\omega_1x+\omega_2x+\omega_3x+\omega_nx-\mu\omega_1y-\mu\omega_2y-\mu\omega_3y-\mu\omega_ny$) away from the crushing piston when the axial component (x) is greater than the perpendicular component (y).

In a horizontal orientation the axial (x) component is zero (0) and the maximum crushing force (C_2) is the fluid force (F_1) less the friction of the piston (μN_1) less the friction of the tubing ($\mu\omega_2y-\mu\omega_3y-\ldots-\mu\omega_ny$) or ($C_2=F_1-\mu\omega_1y-\mu\omega_2y-\mu\omega_3y-\ldots-\mu\omega_ny$), which occurs at the crushing piston and limits tubing compaction.

. Conversely, in a vertical position the perpendicular component (y) is zero (0) and the maximum crushing force ($C_2=F_1+\mu\omega_1x+\mu\omega_2x+\mu\omega_3x-\ldots+\mu\omega_nx$) is at the bottom of the tubing being crushed which will tend to assist tubing compaction by avoiding the pushing of crushed and splayed tubing.

Alternatively, as is the convention for wireline and slickline tool frictions within a liquid filled well bore, it is reasonable to assume that the axial (x) component is greater than the perpendicular (y) component and the maximum crushing force (C_2) can occur at the bottom of the tubing for inclinations of less than 60 degrees.

Conversely, based on the conventional rules of thumb for wireline and slickline friction factors, the maximum crushing force could be somewhere between the crushing piston and the lower end of the tubing being crushed for inclinations over 60 degrees.

Conservatively, based on the present simulation results for Model run [1], which measured helical buckling friction, it is likely that the threshold for crushing friction and transferring the maximum load to the bottom of the tubing will occur at around a 45 degree well inclination.

Accordingly, the 46% compression rates achieved in the “dry” modelling, where friction factors (μ) are at their highest levels, is particularly encouraging because forces resisting crushing will always be less within comparable scenarios, even at inclinations greater than 45 degrees, and especially within a liquid filed vertical or near vertical well bore where gravity associated with the mass of the tubing acts along the axis to transfer loads to the bottom of the tubing and reduces the normal force associated with the friction applied by weight, helical buckling and splaying of crushed tubing.

Modelling Runs

Six (6) modelling runs were performed between the 22nd and 31st of July 2013 which comprised:

[1] Approximately three-hundred and eighty (380) feet of 5 ½” casing within which three-hundred and forty-seven point seven six (347.76) feet of tubing were placed and helically buckled to measure associated frictional factors;

[2] Approximately sixty-three and one half (63.5) feet of tubing with three (3) longitudinal cuts was placed within the above casing and crushed;

[3] Approximately thirty-one point eight (31.8) feet of tubing with six (6) longitudinal cuts was placed within the above casing and crushed;

[4] Approximately ninety four point six seven (94.67) feet of tubing; comprising 31.42 feet of tubing with six (6) longitudinal cuts, 31.67 feet of tubing with three (3) longitudinal cuts, and 31.58 feet of tubing, which was uncut, was placed within the above casing and crushed;

[5] Approximately thirty one point five eight (31.58) feet of tubing with three (3) longitudinal cuts was placed within 5 ½” casing and crushed;

[6] Approximately thirty one point six one (31.61) feet of tubing with six (6) longitudinal cuts, which was severed into approximately three (3) equal portions was placed and crushed within 5 ½” casing.

Physical Model Run [1]

Physical model run [1] was used to calibrate frictional factors within Oilfield Innovation’s internal crushing model for subsequent crushing efforts.

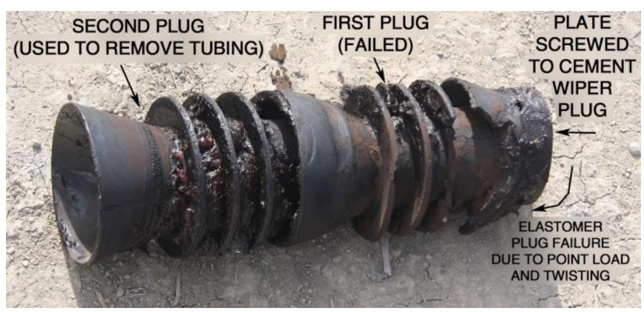

Figure 9 – Model Run [1] Cement Wiper Plug Piston

Figure 10 – Model Run [1] Plastic Deformation Initialized

Model run [1] comprised placing eleven (11) joints of tubing measuring 347.76 feet in length within approximately 380 feet of 5 ½" casing to helically buckle the tubing and determine the associated friction force; wherein a small portion of the tubing buckled, as shown in Figure 10, prior to failure of the casing cement wiper plug and steel crushing plate.

Model run [1] ended with failure of the cement wiper plug, shown in Figure 9, at a pressure of approximately 2,400-psi. The elastomeric wiper plug lacked sufficient axial stability and, consequently, twisted due to point loading of the tubing on one side of the plug. A second cement wiper plug was used to induce minor tubing deformation at a pressure of 2,800-psi; after which the tubing was pumped out of the casing.

Model run [1] succeeded in determining the horizontal frictional forces associated with normal friction and "helical buckling" frictional forces, which resisted crushing to the point of the initialization of plastic deformation shown in Figure 10; wherein a length of approximately three hundred and fifty (350) feet of 2 3/8" tubing placed within 5 ½" casing helically buckled with an associated helical friction equal to the defined piston force less the conventional normal frictional forces associated with the tubing weight.

Tubing Weakening

Oilfield Innovations have patented the weakening of tubing prior to crushing, wherein a wireline tool with axial cutting wheels may be deployed into a well on slickline or electric line to longitudinally cut through and/or partially cut through and weaken the tubing.

A critical aspect of the modelling effort was to determine the effects that longitudinal and transverse cutting of the tubing had on the crushing ratio.

Model runs [2] to [6] involved various weakening scenarios, wherein the tubing was longitudinally cut with a hand held plasma cutter and transversely cut in model run [6] with a saw to simulate downhole cutting of tubing and the subsequent effect upon compaction of the weakened tubing during crushing.

The modelling efforts found that, generally, transverse cuts lead to side-by-side compaction of tubing while longitudinal cuts resulted in a common crushing pattern and/or side-by-side compaction during compaction of the tubing into a smaller space.

Physical Model Run [2]

Model run [2] comprised placing two (2) joints with a length of sixty-three and one half (63.5) feet plus a 3.25 foot centralizing stub for a total of 65.75 feet, wherein three (3) longitudinal cuts were made in the tubing before placing it in the 5 ½" casing and applying 4,000-psi of pressure using an ordinary water wash pump similar to that in Figure 4.

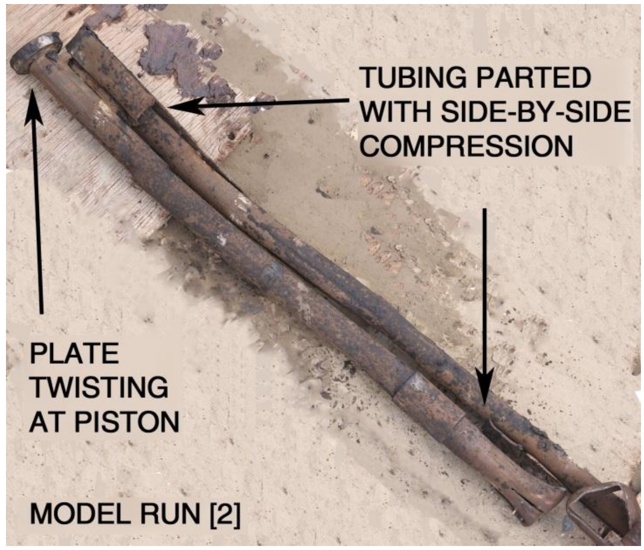

Figure 11 – Model Run [2] Side-by-Side Compaction†

As shown in Figure 11, a one (1) inch thick plate was welded to a stub of tubing to centralize the tubing during crushing, which twisted and caused the piston to fail after the tubing parted and compressed into a side-by-side arrangement.

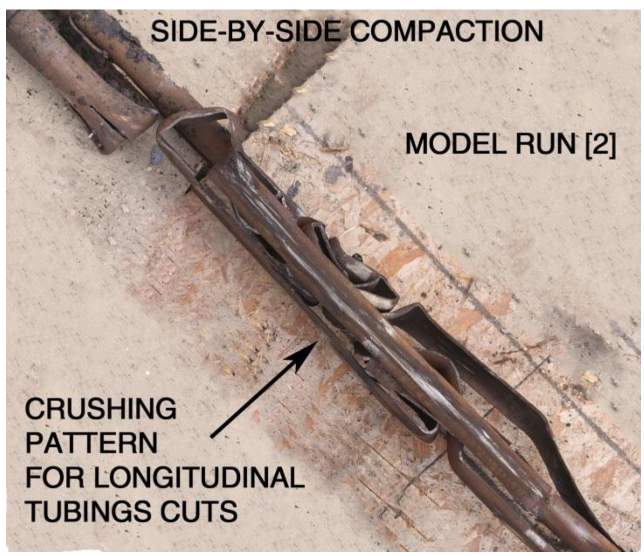

Figure 12 – Model Run [2] Common Compaction Pattern†

The model run [2] crushing pattern shown in Figure 12 occurred below the side-by-side configuration and was common to longitudinally cut tubing for each of the other model runs.

Very small displacement volumes were achieved during application of the 4,000-psi crushing pressure, which destroyed the seals of the common water wash pump when the motor failed to stall out.

Additionally, the twisting of the one (1) inch plate piston prevented axial force transference to the remainder of the tubing, which resulted in approximately a 15.5% compression ratio, wherein the final tubing length was 56.41 feet of its original 66.75 foot length.

Physical Model Run [3]

Model run [3] comprised an attempt to remedy the twisting of the crushing piston with a compactable wooden piston used to crush a single tubing joint approximately thirty-one point eight (31.8) feet long with six (6) longitudinal cuts.

The wet end of the casing was pressured to 1,800-psi before leakage past the piston into the dry end of the casing ended the simulation; after which the tubing, failed piston, and plugs were ejected and the water used to drive the piston was allowed to run out of the casing.

Figure 13 – Model Run [3] Failed Wooden Piston

As shown in Figures 13 and 14, a wooden plug, which was stronger than the elastomer plugs, also failed under point loading of the tubing, which ultimately caused the piston and wiper plugs to fail at a tubing compaction ratio of 11.8%, wherein the original 31.80 foot length was compressed to a 28.12 foot length.

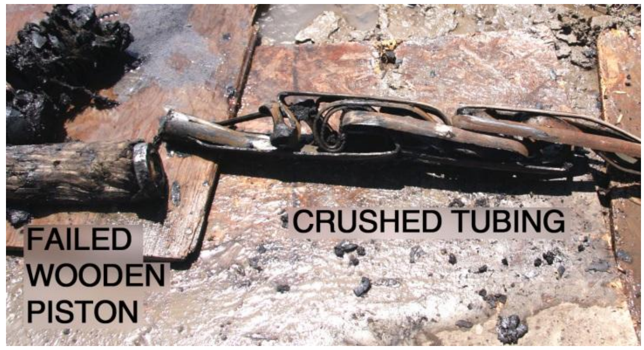

Figure 14 – Model Run [3] Common Compaction Pattern

The model run [3] tubing compaction pattern for longitudinal cutting of the tubing was similar to model run [2], whereby the three (3) longitudinal cuts of run [2] and six (6) longitudinally cuts of run [3], shown in Figures 12 and 14, respectively, have similar crushing patterns.

Physical Model Run [4]

Model run [4] comprised three (3) tubing joints, totalling approximately ninety four point six seven (94.67) feet in length, wherein the lower 31.42 feet of tubing was weakened with six (6) longitudinal cuts, the next 31.67 feet of tubing was weakened with three (3) longitudinal cuts, and the upper 31.58 feet of tubing was uncut prior to placement within the 5 ½” casing.

In contrast to the previous model runs where crushing ended with the failure of the crushing piston, an improved piston was used. The piston comprised convention schedule 80 pipe with a 4 inch internal diameter and 4.5 inch outside diameter placed within the 4.778 inch 5 ½” casing internal diameter. The piston was approximately 20 inches long and had plates welded on both ends.

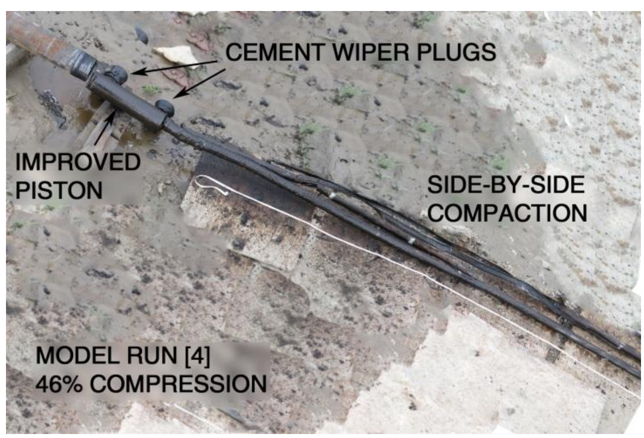

Figure 15 – Model Run [4] with side-by-side compaction†

As shown in Figure 15 above, the improved piston allowed continued crushing to a pressure of 5,800-psi and resulted in a compression rate of 45.9% with the final crushed tubing length being approximately 51.4% of its original length or 51.24 feet of its original 94.67 foot length.

In a manner similar to model run [2], the tubing compacted in the side-by-side arrangement shown in Figure 15, wherein the uncut tubing was compacted through the tubing with three (3) longitudinal cuts, which in turn compressed the tubing with six (6) longitudinal cuts into a pattern similar to that seen in previous model runs. Part of the steel's elastic properties remained and the tubing to expand once it was ejected from the casing, as shown in Figure 16.

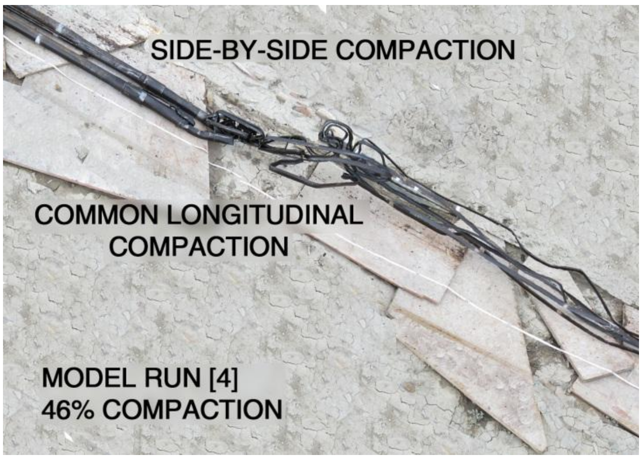

Figure 16 – Model Run [4] longitudinal cut compaction†

As the compacted tubing retained some of its elastic nature and tended to expand as it was pushed from the casing using the piston and cement wiper plugs, the compaction ratio may have been marginally higher prior to ejection from the casing.

Physical Model Run [5]

Model run [5] was performed to measure compaction prior to ejection from the casing, but the cement wiper plug seal failed at 4,200-psi and the test was stopped. Model run [5] comprised approximately thirty one point five eight (31.58) feet of tubing with three (3) longitudinal cuts placed within a single joint of 5 ½" 20-ppf casing.

As shown in Figure 17, the horizontal orientation of the casing caused significant crushing to occur close to the piston with less compaction at the lower end.

The overall compacted tubing length of 17.17 feet compared to the original length of 31.58 feet comprised a calculated 45.6% compression ratio.

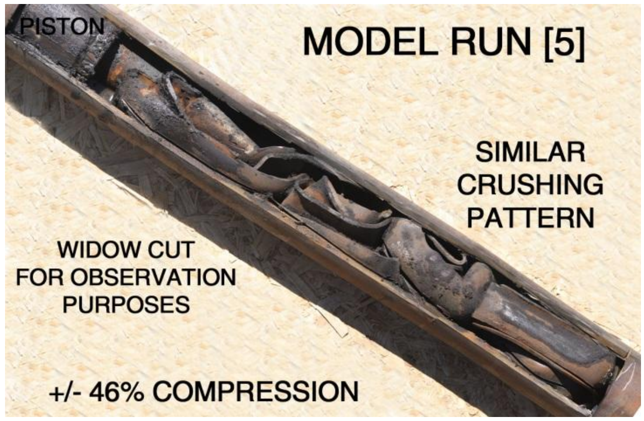

Figure 17 – Model Run [5] – Observation Window in Casing†

A window was cut in the casing to observe the in-place compacted tubing, as shown in Figure 17; wherein it was obvious that the longitudinally cut tubing can be compacted even within "dry" casing.

Physical Model Run [6]

Based upon the side-by-side compaction and longitudinal compaction patterns displayed in model runs [2] to [5], model run [6] was designed to combine the two observed effects by splitting a thirty one point six one (31.61) foot joint of tubing with six (6) longitudinal cuts into approximately three (3) equal axial portions and compacting it within a single joint of casing.

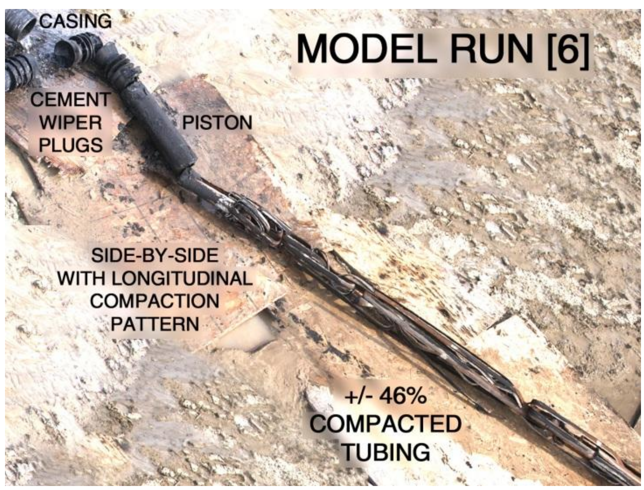

Figure 18 – Model Run [6] – Combined Compaction Pattern†

As shown in Figure 18, the original tubing joint length of 31.61 feet was crushed into a compacted length of approximately 17.19 feet for a calculated 45.6% compaction ratio, which was achieved with a piston pressure of 3,000-psi, which was notably lower than the pressures needed in model runs [4] and [5].

Conclusions

The results from physically simulating worst case well abandonment conditions using Oilfield Innovation's patented and patent pending process for weakening and crushing tubing were exceptionally encouraging because a 46% compression ratio was achieved within three (3) separate model runs despite using a horizontal crushing scenario in a "dry" casing space with only common household equipment.

Figure 19 – Model Run [6] – Combined Failure†

Physical modelling demonstrated that OILtd's patented process for longitudinally cutting the tubing to provide for compaction through both side-by-side and plastic deformation is viable, wherein conventional slickline and/or electric line oilfield tools can be fitted with rolling wheel cutters and axially moved within the tubing to effectively shred it into spaghetti-like strands that can be compacted like the Figure 19 tubing.

Accordingly, the compaction of tubing can be controlled through well engineering to riglessly provide an unobstructed space for logging casing cementation and placing a rig equivalent well abandonment plug that meets U.S. BSEE, Texas Railroad Commission, Oil & Gas UK, and NORSOK requirements.

The modelling efforts indicated that the maximum compaction forces within oil and gas wells with an inclination below 45 degrees will occur at the lower end of the tubing being crushed and will continue until the piston crushes the entire tubing length. In well bores with inclinations exceeding 45 degrees, the simulations indicated that a number of crushing runs would be necessary to, for example, form a 330-ft or 100 metre length of unobstructed casing for logging and cementation using the mothod of model run [4].

Simulations were physically carried out with low volume pumps to demonstrate that the frictional effects of tubing buckling and splaying can be overcome with minimal equipment within the worst case friction conditions. Model runs demonstrated that for well inclinations between 45 degrees and horizontal a number of smaller compaction stages with a number of longitudinally and/or transversely tubing cuts can be used to achieve acceptable downhole compaction ratios and associated unobstructed space within the casing.

For example, for cement supported by the crushing pistion, 165 feet or 50 metres of unobstructed casing in a near horizontal well bore section could be used to meet NORSOK requirements. In this scenario, model run [4] could be replicated using approximately 357 feet or 109 metres of tubing longitudinally and/or transversely cut and compressed in four 90 foot or 27 metre runs to provide the required unobstructed space.

One of the most exciting aspects of the simulation are potential for engineered solutions and the upside potential of using oilfield specification equipment instead of the hardware store variety used within the present modelling runs.

It was evident when observing the pressure build-ups during each model run that an oilfield grade pump with a high displacement rate could maintain crushing momentum and negate small leaks past the piston to increase tubing compaction significantly.

Finally, as the physical volume of steel tubing within casing is generally between 15% and 20% of the overall volume, the results indicated that the crushing of tubing within a near vertical arrangement of a liquid filled oil and gas well using oilfield grade equipment could achieve compression ratios significantly greater than 46%, which could approach, for example, over 60% compaction based upon the visual observation of open space within the various crushed sections of model runs [2] to [6].

Acknowledgements

Special thanks are given to Arnold, Lloyd and Eric Tunget for contributing their time, facilities and

equipment to the carry out the modelling efforts, as well as Eleanor and Joan Tunget for contributing their time and creativity to the project.

Figure 20 Clint Smith and Arnold Tunget

Oilfield Innovations Limited would also like to thank the vendors Summit Mechanical Company of Delta Colorado and Western Slope Plumbing and Welding of Montrose Colorado for providing services at crucial points during the modelling.

Figure 21 Oilfield Innovations Directors C. Smith, B. Tunget

Further Information

For investment opportunities in Oilfield Innovations Limited's patents and patent pending technology please see www.oilfieldinnovations.com or contact Clint Smith or Bruce Tunget on the below email address or phone.

Notes and references

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† Various photograph series were merged into a single photograph to illustrate a relevant length of tubing.

‡ Footnotes.

1 The U.S. Bureau of Ocean Energy Management , Regulation and Enforcement (BOEMRE) was formerly the Minerals Management Service (MMS), wherein MMS CFR-2007 Title 30 Volume 2 Section 250 subsections 1712 to 1715 apply to well abandonment.

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