OTC-30421-MS

A New Solution for Well Abandonment: Bismuth and Thermite

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This paper was prepared for presentation at the Offshore Technology Conference Asia originally scheduled to be held in Kuala Lumpur, Malaysia, 17 - 19 August 2020. Due to COVID-19 the physical event was postponed until 2 – 6 November 2020 and was changed to a virtual event. The official proceedings were published online on 27 October 2020.

Abstract

Well abandonment is as much a part of the oil and gas industry as drilling and production yet is seems to receive the least amount of consideration. Operators spend months and even years planning how they will drill and complete a well but often don't think about how they will abandon it until production has ceased. As such, they tend to rely on traditional methods and materials, doing it the same way it has always been done and yielding the same results which are often not desirable. Recently, more operators have chosen to spend more time planning well abandonments than ever before. Perhaps this is because the requirements for well abandonment have increased or because, unlike drilling and production, any money spent on well abandonment comes straight off the bottom line without the opportunity to recuperate during production. Either way, this increase in visibility has led to a search to abanon wells more efficiently and cost effectively.

One of the ways to achieve this is by looking at alternative sealing materials, such as bismuth. Since 2015, bismuth alloy tools have been delployed over 80 times to seal wells at various stages of the well's life with 60% of the tools run for well abandonment. Bismuth alloys are also being considered as possible alternative barriers to cement by multiple regulatory agencies.

Statement of Theory and Qualification Testing

Bismuth has multiple commercial uses outside of the oil and gas industry. It is used as an alternative to lead for solder and shotgun pellets and is the main active ingredient in Pepto-Bismol. The idea of utilizing bismuth for sealing in downhole environments is also not new, the earliest patents go back to the 1930's. For the past 80+ years, there have been many attempts to utilize bismuth as a downhole sealing material due to its unique properties:

- It has a relatively low melting point compared to other metals (273 °C).
- When in liquid form (melted) it has a viscosity very similar to water.
- It is very dense with a specific gravity of 10.
- It is non-corrosive and not affected by H2S or CO2.

- Upon solidification, it expands approximately 3%, similar to how water expands when it turns to ice.
- It is non-toxic, used in place of lead in some commercial applications for this quality.
- It is a eutectic metal that goes from a liquid to solid state almost instantaneously when it cools below its melting point, bypassing the gel phase.

The challenge in creating a seal with bismuth has always been how to deploy it downhole, melting it then getting it to solidify and expand where the seal is required. Previous attempts were all made with electrical heaters. These heaters would require large amounts of power (480V and 11A to generate 540KJ of energy) for hours to melt a relatively small amount of bismuth alloy. Due to voltage drops in electric line, this limited the depth at which the tool could be run in the well. After melting, the electrical heaters could not keep the bismuth in the liquid phase long enough for it to reach the sealing area and fill the entire void where it was intended to seal.

In order to obtain the necessary energy, the idea of thermite was introduced as a heating element. Thermite is a combination iron oxide and aluminum powder. When put together in the correct chemical composition and activated, a chemical reaction occurs resulting in biproducts of aluminum oxide, iron and large amounts of heat. To activate the chemical reaction, thermite must be heated to a temperature above of 2,000 °C and the resultant heat output is in excess of 10,000KJ. The temperature at which the thermite burns can reach as high as 3,000 °C. These temperatures are ideal for its main commercial use, welding railroad tracks, but much too high to be utilized downhole as the steel components in the well could be affected. For the thermite heating element to be properly utilized with the bismuth, the burning temperature would have to be controlled and consistent. To do this, binding and damping agents were added to the thermite. The binding agents ensure the chemical composition or iron oxide and aluminum powder remaine consistent without separating, resulting in a consistent and repeatable reaction. The damping agents control the amount of heat generated and the speed at which the reaction takes place. The idea was to create a thermite heater that would function like an electrical heater with a higher energy output. This was achieved with the "modified thermite" mixes. These mixes burn at temperatures ranging from 200 °C to 800 °C and burn times from 15 seconds to 45 minutes. To alleviate the issues related to depth limitations and power supplies, a "starter" was developed to initiate the chemical reaction within the heater using 240V and 60mA for 15-30 seconds. By doing this, the tools could be run on standard electric line with the same power requirements as a perforating gun or wireline set bridge plug. As this heat is generated thorugh a chemical reaction, it is non-explosive and does not require any permits or special handling. This allows for a rigless solution that not only saves the operator money, it also reduces the footprint required on location and safety risks associated with operations run from a rig.

After combining bismuth with the modified thermite heaters, it became evident that a 273 °C melting point material was not ideal for all well environments. To control the solidification process and ensure the bismuth would fill the sealing area, solidify and expand, the wellbore fluid must be used as a cooling agent to extract the heat from the bismuth. If the wellbore fluid is too cool, the bismuth would solidify too fast and a seal would not be achieved. To combat this, bismuth "alloys" were developed. By adding small amounts of other metals to the bismuth, the melting temperature could be altered. Alloys with melting temperatures ranging from 93 °C to 263 °C were created. Through liquidous/solidous tests and polish tests to analyze the grain structure of the alloys, these alloys were found to consistently exhibit the same unique qualities of bismuth that are listed above. Combining these alloys with the modified thermite heaters, gas tight seals are now being created in wellbores with temperature ranges from 4 °C to 150 °C.

The tools are assembled by casting alloy on the outside of the heater. The tool is then run in the well to depth on electric line. Once on depth, using a casing collar locator, 240V and 60mA is placed down the electric line for 15-30 seconds. The power is transferred to the starter, which in turn heats up to over 2,000 °C and starts the chemical reaction inside the heater. The heater burns from the top down, similar to a wick in a candle. As the heater burns, it melts the alloy at the top of the tool first. This molten alloy runs down the side of the tool, again similar to wax on a candle. As it reaches the bottom of the tool below the heater where it is no longer has a heat source, and is being cooled by the wellbore fluid, it solidifies around the base of the tool and forms a base within the tubing/casing/open-hole. The heater continues to burn towards the bottom, melting the alloy on the outside of the tool. This liquid alloy pools up on top of the base that was formed and around the heater. As the chemical reaction reaches the bottom of the heater, it also begins to cool at the top. The liquid alloy takes the shape of the area it is sealing and the top part of the alloy is the first to solidfy. When the remainder of chemical reaction is complete, the remainder of the alloy cools and begins to expand. With the bottom and top sections both solidified, this alloy can only expand radially against the tubing/casing/open-hole. This expansion creates a gas tight seal and also anchors the tool in place through friction. There is no chemical bond between the alloy and the tubing/casing/open-hole, only radially loading and friction.

When the theory of putting bismuth and thermite together first came about, the idea was to create a gas tight bridge plug in tubings where conventional well abandonment materials had not always been successful. During well abandonment, it is important to stop the flow of gas as close to the source as possible. This is accomplished by either squeezing the producing formation with cement or placing a bridge plug in the tubing directly above the producing interval. With that in mind, and the development of modified thermite heaters and bismuth alloys, the concept was first tested inside a piece of 4 ½" tubing. The result was a seal that was successfully tested and qualified to ISO 14310 V0 at 65 °C and 5,000 psi. The test was conducted as follows:

- The bismuth-based alloy with a 138 °C melting point was cast on the outside of a 2 7/8" OD steel mandrel.
- The 2 3/8" heater was loaded with a modified thermite mixture and a starter.
- The heater was placed inside the mandrel and held in place with brass shear pins.
- Thermocouples were attached to the outside of a 4 ½" tubing.
- An end cap with a thermocouple and pressure control line was assembled to the bottom of the 4 ½" tubing.
- The 4 ½" tubing was lowered into a test pit and filled with water.
- The bismuth and thermite tool was lowered into the 4 ½" tubing.
- An end cap with a thermocouple and pressure control line was assembled to the top of the 4 ½" tubing and the wires from the starter were run through the top of the end cap.
- The test vessel was pressured to 3,000 psi and heated to 65 °C.
- The heater was activated through a firing box at surface, providing 240V and 60mA for 15 seconds.
- 3,000 psi pressure and 65 °C were maintained for 2 hours.
- The test vessel was allowed to cool to ambient temperature (23 °C) after the 2-hour hold.
- The heater was removed from the mandrel by shearing the brass shear pins.
- The test vessel was heated to 65 °C.
- An ISO 14310 V3 pressure test to 5,000 psi differential was conducted successfully at 65 °C from both above and below the seal, maintaining less than 1% decrease in pressure over 15-minute intervals from each direction.
- A bubble cup was tested for leaks and assembled to the top pressure control line.

- An ISO 14310 V0 gas test to 5,000 psi differential was conducted successfully at 65 °C from below with no bubbles seen in the bubble cup over a 15-minute interval.
- The bubble cup was tested for leaks and assembled to the bottom pressure control line.
- An ISO 14310 V0 gas test to 5,000 psi differential was conducted successfully at 65 °C from above (reversal #1) with no bubble seen in the bubble cup over a 15 minute interval.
- The bubble cup was tested for leaks and assembled to the top pressure control line.
- An ISO 14310 V0 gas test to 5,000 psi differential was conducted successfully at 65 °C from below (reversal #2) with no bubbles seen in the bubble cup over a 15 minute interval.
- The test vessel was alloed to cool to ambient temperature (30 °C).
- An ISO 14310 V0 gas test to 5,000 psi differential was conducted successfully at ambient temperature from below with no bubbles seen in the bubble cup over a 15 minute interval.
- The bubble cup was tested for leaks and assembled to the bottom pressure control line.
- An ISO 14310 V0 gas test to 5,000 psi differential was conducted successfully at ambient temperature from above (reversal #3) with no bubble seen in the bubble cup over a 15 minute interval.
- The test vessel was heated up to 65 °C
- The bubble cup was tested for leaks and assembled to the top pressure control line.
- An ISO 14310 V0 gas test to 5,000 psi differential was conducted successfully at 65 °C from below (reversal #4) with no bubbles seen in the bubble cup over a 15 minute interval.
- The test vessels was allowed to cool to ambient temperature.

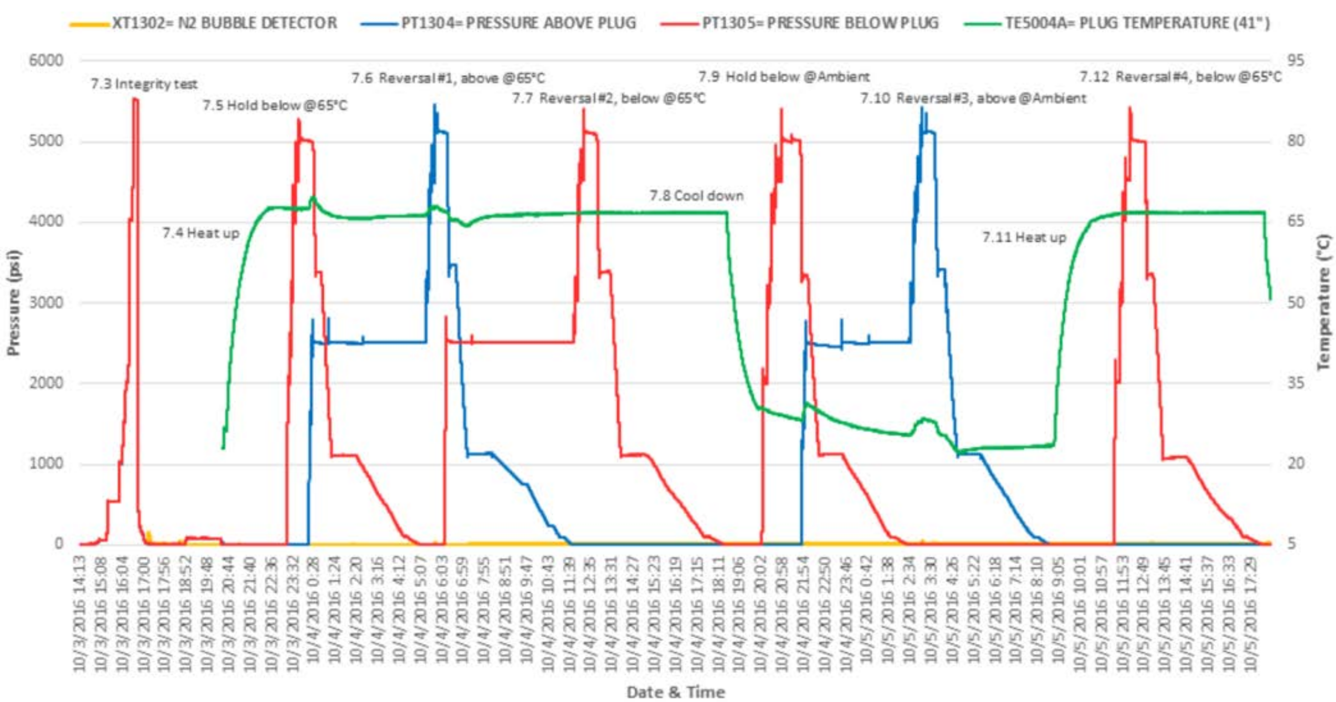

Figure 1—V0 Testing Full Duration

Applications of Bismuth and Thermite

After qualification to ISO 14310 V0 was complete, the tool was ready for field deployment. It was first deployed in a total of 12 test wells in Oklahoma, United States. Each of the tools run were the same as the one tested above but were run under different well conditions. They were set inside 4 ½" tubing at depths ranging from 2,000' to 8,000' and deviations up to 50°. After setting, each was pressure tested to 5,000 psi from surface. After pressure testing, the tubing was retrieved from each well in order to evaluate the seal that had been created.

Figure 2—Retrieved Bismuth Seal Set Inside Tubing

After successful field trials in Oklahoma, the tools were run in 2 wells in Alaska. These tools were run under the same condition as in the Oklahoma wells for zonal isolation during well abandonment.

Three more tools were then run for zonal isolation during well abandonment. The first two tools were set in the Norway sector of the North Sea. In each of these two wells, the producing zone had been isolated with a V0 rated mechanical bridge plug and cement. After placing the cement, the wells continued to bubble gas up the tubing and build surface pressure up to 1,200 psi. These bismuth tools were set in a 5" liner and pressure tested to 4,000 psi. A 24-hour leak test was conducted on each with no pressure or bubbles seen at surface.

Figure 3—Bismuth Seal Leak Test Compared to Bridge Plug and Cement

The third tool was set in the UK sector of the North Sea. On this well, the 5" tubing had a kink in it that restricted the ID of the tubing above the setting depth to a 3.1" ID. The operator had previously set two V0 rated high expansion mechanical plugs, but gas continued to leak past them to surface. The bismuth tool was set inside the 5" tubing, pressure tested to 1,400 psi and negative pressure tested for 1 hour with no bubbles or pressure seen at surface.

With successful tool deployments inside of tubing, the idea of sealing in multiple annuli with bismuth was the next step. The first bismuth tool to be deployed for sealing not only inside tubing but also in a tubing by casing annulus took place in the Norway sector of the North Sea. This well, with 4 ½" tubing and 7" production casing, had been temporarily abandoned by setting a V0 rated mechanical bridge plug in the tubing. The tubing was also perforated above the bridge plug and a cement balance plug was placed in the tubing and production casing annulus. The cement was underdisplaced, leaving cement in the tubing higher in the well than in the annulus. Similar to the previous well abandonments mentioned above, this well continued to build surface gas pressure in the tubing, as well as in the annulus. The tubing was perforated above the cement in the tubing and a bismuth tool was run in the well across the perforations. Once the heater was activated, the alloy melted and solidified at the bottom of the tool as described above. Once the remainder of the liquid alloy pooled up inside the tubing reached the perforations, it flowed out into the annulus. In the same manner as in the tubing, when it reached below the heater and was cooled by the wellbore fluid, it created a base in the annulus as well. The remainder of the liquid alloy pooled up in the annulus, solidified and expanded to create a gas tight seal in the well. This seal was pressure tested to 4,000 psi and a negative pressure test was completed for one hour with no pressure or bubbles seen at surface.

Since these initial deployments, run mainly as field trials, bismuth alloy plugs are being routinely run to create a gas tight barriers during well abandonment. Recently, bismuth alloy plugs were utilized in each well of a 15 well P&A campaign and are currently being run in each well of an ongoing 20 well P&A campaign. At this time, cement is still being placed on top of each of these plugs to meet regulatory requirements, but qualification programs are ongoing for bismuth alloys to be recognized as an alternative to cement in well abandonment. Although not currently accepted as a barrier material by regulators, operators are utilizing bismuth alloy plugs rather than relying on cement when there are known gas sources in the well, seeing this as an opportunity to reduce their liability and environmental impact by ensuring their wells are properly sealed and will remain that way long after decommissioning is complete.

Conclusion

Well abandonments are a necessity in the oil and gas industry. While operators have done a great job with this over the past decade, many wells throughout the world still remain. With the recent state of the oil and gas industry and growing environmental concerns, it is more important now than ever to abandon wells properly and permanently the first time. Given the limitations of cement, bridge plugs and resins, a more reliable plugging material has been needed for years and now there is one; bismuth and thermite.