Appendix Q. Summary of The Effect of Spacer Fluid Composition and Placement on the Negative-pressure Test

Summary

Scope

During the second negative-pressure test, 1,400 psi of pressure was seen on the drill pipe gauge while no flow was recorded from the open kill line. This appendix evaluates whether the properties and placement of the spacer that was pumped as part of the Macondo well displacement could have plugged the blowout preventer (BOP) kill line and/or masked the results of the second negative-pressure test.

Spacer Displacement Plan

The M-I SWACO mud engineer prepared a written procedure for the displacement of the drilling mud from the well and riser. The plan was to suspend the displacement part way through so that a negative-pressure test could be conducted to confirm the integrity of the recently set and cemented 9 7/8 in. x 7 in. casing string. The intent was to place the spacer just above the BOP stack before starting the negative-pressure test.

Spacer Formulation

The spacer was a combination of two lost circulation material (LCM) pills that were mixed approximately two weeks prior to the accident. These pills were mixed in preparation for losses that could have occurred while drilling the previous hole section, but they were not required. The decision to blend the two LCM pills to provide a displacement spacer was driven by the opportunity for the beneficial re-use of the materials. After the two spacers were blended together, barite and DUO-VIS (xanthan gum viscosifier) were added to meet required properties. While there was no specific viscosity requirement, the M-I SWACO mud engineer knew that the resulting fluid was sufficiently viscous. The mud engineer added the additional DUO-VIS in the final stages of spacer preparation on April 20, 2010.

Notes from a witness interview of an M-I SWACO mud engineer indicate the following:

> Two water-based pills; 1 FORM-A-SQUEEZE - in pit 3; 1 FORM-A-SET™ - in pit 5 were mixed together to make one big spacer in pit 5. There was 425 bbls pumpable.
> . . . increased the weight to 16 ppg and added 2 sacks of DUO-VIS (108 lbs.)
> It was too thick to measure the rheology.
> . . . intent was to put spacer above the BOP to facilitate the negative test
> FORM-A-SET™ and FORM-A-SQUEEZE mixed together and used as a spacer was not standard.

After the boost, choke and kill lines were displaced to seawater, the displacement of the well began as planned. Real-time data indicates that the volume pumped was sufficient to place the spacer 12 ft. above the top of the BOP.

The spacer was displaced with around 30 bbls of fluid, which M-I SWACO in their information to the investigation team indicated was fresh water, but it may also have been tank washings from the spacer tank followed by seawater. *Table 1* shows what was actually pumped.

Table 1. Planned versus Actual Volumes Pumped.

Line	Planned (bbls)	Actual (bbls)
Booster (seawater)	73	79
Choke (seawater)	100	110
Kill (seawater)	100	106
Material	**Planned (bbls)**	**Actual (bbls)**
Spacer	425 (16 ppg)	424 (16 ppg)
Fresh water or pit wash	0	30
Seawater	350	352
Total volume	**775 bbls**	**806 bbls**

The positions of the fluids when the pumps were stopped for the negative-pressure test, based on real-time data, are shown in *Table 2.*

Table 2. Fluid Heights Prior to Negative-pressure Test.

Fluid	Height
Top of spacer	3,718 ft. below rotary table (BRT)
Base of spacer	4,989 ft. BRT (12 ft. above the top of the BOP)
Base of fresh water/pit wash	5,264 ft. BRT (210 ft. below the base of the BOP)
Base of seawater	8,367 ft. BRT

At the cessation of pumping, the additional 30 bbls of fresh water/pit wash would have been across the kill line entry point. In addition to this, the annular preventer leaked when it was closed in preparation for the negative-pressure test. This resulted in another approximately 50 bbls (based on real-time data and witness accounts) of the spacer fluid passing down through the leaking annular preventer into the BOP, across the choke and kill line entry points and into the annulus below.

The Transocean subsea supervisor, who was on the rig floor at the time, testified during the May 28, 2010, Marine Board of Investigation (MBI) hearing:

> "During the negative test, they felt like they lost approximately 60 barrels of mud through the annular. They increased the regulator pressure to 1,900 and it stopped leaking."
>
> "[Toolpusher] was convinced we lost 60 barrels of mud through the annular. They bumped the annular up to 1,900 and they [weren't] losing any more."

After some concern about the validity and method used for the first negative-pressure test, a second test was conducted. Witness accounts indicate that, during the first test, 3 bbls to 15 bbls of fluid was bled into the kill line.

Referring to the first negative-pressure test, notes from an interview with a BP well site leader indicate:

> We discussed the kill line thing [lack of pressure]. I said we need to monitor on the kill line. Let's open the kill line and see what happens—it started to flow. The cementer called and said it had started to flow. I said shut it in we could have an overbalance. I will talk to [well site leader] and see what he wants to do.
>
> I think they closed the IBOP. Bled 3–4 barrels off the kill line and I told him to shut it in.

This fluid was then left static in the kill line while discussion and preparation took place for the second negative-pressure test.

Conclusion

The investigation team has concluded that, because the spacer was inadvertently placed across the kill line inlet, solids from the spacer may have plugged the kill line. Alternatively, either the viscosity or gel strength of the spacer, or both, could have been too high to allow proper pressure transmission through the kill line. Either case could have complicated the interpretation of the negative-pressure test.

A full description of the spacer properties investigation follows.

1 Introduction

As part of the investigation into the events leading to the release of hydrocarbons and the subsequent explosion on *Deepwater Horizon* while drilling the Mississippi Canyon Block 252 (Macondo) well, a fluids-specific study was performed. The primary objective of this investigation was to determine if the spacer used for displacement of the riser from the mud to seawater could have contributed to the inability to detect pressure at the kill line.

Spacer Study *Terms of Reference*:

Objective: Determine the likelihood that the fluids and/or mixing of fluids used in the negative-pressure test could have caused plugging in the BOP area.

Action Steps:

1. Identify what fluids were pumped into the well.
2. Confirm what volumes of fluids were pumped into the well.
3. Identify what compatibility tests were requested by the BP Macondo well team and completed by the fluids service provider.
4. Complete compatibility tests for all fluids to establish how the fluids would react with each other, giving due consideration to temperature and pressure effects.
5. Identify what settlement of solids could take place in various volume, pressure and temperature regimes, especially in small bore lines. Establish whether solids could have settled out in the BOP kill line during the negative-pressure test.
6. Analyze mud samples received from M/V *Damon Bankston* to establish if deck samples are synthetic oil-based mud (SOBM).
7. Establish how much drilling fluid had been offloaded from the rig to M/V *Damon Bankston* and how much drilling fluid was still on the rig.
8. Identify if there was a visible difference between the SOBM and the spacer used in the well, and establish (if possible) what was coming out of the well at the time leading up to and during the evacuation.

2 Conclusions

The conclusions are set against the *Terms of Reference*.

1. Identify what fluids were pumped into the well.

- Kill, choke and riser boost lines were over-displaced to 8.6 ppg seawater.
- The spacer was a water-based, 16 ppg blend of previously mixed LCM materials. Based on reports from M-I SWACO mud engineers, the investigation team believes that a ratio of approximately 62/38 vol/vol of FORM-A-SET™ AK -to- FORM-A-SQUEEZE was mixed on the rig to 14 ppg as a lost circulation contingency on April 6, 2010. The decision to blend these two LCM pills to provide a displacement spacer was driven by the opportunity for beneficial re-use of these materials. After blending, the combined spacer was weighted-up with barite and DUO-VIS (xanthan gum viscosifier) to meet the required properties in terms of density and, while there was no specific viscosity requirement, the M-I SWACO mud engineer knew that the resulting fluid was sufficiently viscous. The M-I SWACO mud engineer added the additional DUO-VIS in the final stages of spacer preparation on April 20, 2010.

- The displacement simulation completed for this study shows that, at the pump rates used, the spacer should have provided efficient displacement of the SOBM. However, this study found no documentation of compatibility testing of the spacer with the SOBM or consideration of the long-term stability of the interface between the 16 ppg spacer and seawater.
- The exact formulations of the FORM-A-SET™ AK and FORM-A-SQUEEZE as mixed on April 6, 2010, could not be identified due to incomplete inventory records from the rig. However, the formulations for both materials were consistent with notes from an interview with the M-I SWACO mud engineer and the company's published recommendations. Therefore, the investigation team believes that the formulations used for the laboratory work in this investigation were sufficiently representative of the spacer used in the displacement on April 20, 2010. The weight-up and addition of viscosifier were done in accordance with statements made by the mud engineer.
- The spacer was displaced with around 30 bbls of fluid, which M-I SWACO informed the investigation team was fresh water, but may also have been tank washings from the spacer tank followed by seawater.
- The FORM-A-SQUEEZE contains fibers in excess of 1 mm. FORM-A-SET™ also contains fibers; the exact size of these is not known, but they are believed to be considerably smaller than those in the FORM-A-SQUEEZE.
- The rheology of the most probable blend of the two systems as measured on a Fann 35 rotational viscometer is provided in *Table 3*.

Table 3. Fluid Rheology.

Property	120°F	45°F
600 rpm	203	682
300 rpm	134	358
200 rpm	105	242
100 rpm	71	157
6 rpm	18	39
3 rpm	13	30
PV cP	69	324
YP lbs/100 ft^2	65	33
Gels lbs/100 ft^2	13/24/25	31/38/44

- Note: At 45°F, the 600 rpm and 300 rpm readings were extrapolated from the Bingham hydraulics model.
- Although this material was viscous, the low-end rheology was not particularly high.

2. Confirm what volumes of fluids were pumped into the well.

Table 4. Planned versus Actual Fluids Pumped.

Line	Planned (bbls)	Actual (bbls)
Booster (seawater)	73	79
Choke (seawater)	100	110
Kill (seawater)	100	106
Material	**Planned (bbls)**	**Actual (bbls)**
Spacer	425 (16 ppg)	424 (16 ppg)
Fresh water or pit wash	0	30
Seawater	350	352
Total volume	**775 bbls**	**806 bbls**

The heights of the actual fluid pumped at shut down for the negative-pressure test, according to real-time data, are shown in *Table 5*.

Table 5. Fluid Heights Prior to Negative-pressure Test.

Fluid	Height
Top of spacer	3,718 ft. BRT
Base of spacer	4,989 ft. BRT (12 ft. above the BOP)
Base of fresh water/pit wash	5,264 ft. BRT (210 ft. below the base of the BOP)
Base of seawater	8,367 ft. BRT

Thus, as pumping ceased, the additional 30 bbls of fresh water/pit wash should have been in the vicinity of the kill line entry point.

3. Identify what compatibility tests were requested by the BP Macondo well team and completed by the fluids service provider.

- This material is sold by M-I SWACO for lost circulation and has no history or testing for use as a spacer. No evidence of compatibility testing could be found for the Macondo well.
- Interviews with the BP Macondo well team indicated that pumping this material as a spacer was viewed as beneficial re-use.

4. Complete compatibility tests for all fluids to establish how the fluids would react with each other, giving due consideration to temperature and pressure effects.

- Using a cement/spacer compatibility test, a blend of the spacer was mixed with SOBM provided to the investigation team. A 95/5 vol/vol ratio was selected at a test temperature of 45°F. No indications of unusual behavior were observed.
- When testing for cement compatibility with spacers, the investigation team planned to use vol/vol ratios of 95/5, 75/25, 50/50, 25/75 and 5/95. It concluded after discussions with a global cementing sector specialist prior to this work that, although there would be viscous reactions in the ratios from 75/25 – 50/50 (SOBM to a water-based fluid), it would be more realistic to test for unusual behaviors at the low levels of contamination as representative of the field.
- While it is possible that testing at a higher ratio may have shown a more adverse effect, the viscosity and density contrasts between the SOBM and the spacer indicated this was unlikely to occur. This was supported by BP's basic displacement modeling software.
- The impact of the SOBM/spacer interface as tested did not appear to explain the high pressure required to break circulation after the negative-pressure test.
- Specific compatibility of the spacer with seawater was not performed, as blending the spacer with seawater was part of the settlement work. No impacts beyond what were expected from dilution were observed when seawater was added to the spacer.

5. Identify what settlement of solids could take place in various volume, pressure and temperature regimes, especially in small bore lines. Establish whether solids could have settled out in the BOP kill line during the negative-pressure test.

Gravitational settlement of solids

- The test method used for this work did not allow easy testing at the estimated BOP temperature of 45°F. Thus, the work was carried out at room temperature (68°F).
- The spacer as pumped showed minimal potential to settle solids under gravity.
- With increasing levels of dilution with seawater, the rate of sedimentation increased. With a 50/50 blend, sedimentation began immediately. After 2 hours, there was a densified fluid bed. Overnight, there was a clear separation of phases. A 75/25 seawater to spacer blend showed complete separation in 40 minutes.
- For solids in the spacer to settle, the spacer would have had to mix with the seawater/fresh water below it during placement. Simulation of the placement of the spacer using the BP displacement software showed that this was not likely. It is, however, likely that 16 ppg spacer interface above seawater/fresh water would not have been stable and that rapid mixing would have occured. An accurate simulation of this was not possible within the time frame of this initial investigation.
- Between 59 minutes and 106 minutes after the cessation of pumping the spacer, the kill line was opened to the Halliburton unit, with a flow of 3 bbls to 15 bbls into the kill line. This would have allowed significant intermixing of the spacer and seawater/fresh water to occur in the well prior to opening the kill line.
- Approximately 137 minutes after the cessation of pumping the spacer, the kill line was bled from 30 psi to 0 psi with a return of 0.2 bbls. From the point of fluid ingress into the flow line (between 59 minutes and 106 minutes after the pumping of spacer ceased) and this bleed down, sedimentation in the line would have to occur.

- The investigation team's estimation of fill on the kill line after this ingress was 150 ft. The spacer as pumped contained approximately 30% by volume solids. Using this value:
  - 150 ft. of intact spacer would settle to approximately 60 ft. above the bottom of the kill line.
  - 150 ft. of 50/50 spacer/seawater would settle solids to approximately 30 ft. above the bottom of the kill line.
  - 150 ft. of 75/25 spacer/seawater would settle solids to approximately 15 ft. above the bottom of the kill line.
- The estimations above are theoretical, as the spacer contains low-density fibers that would float in seawater. However, the largest solids fraction is barite.
- Even if the solids settled out of the spacer, it is not definitive that this could have caused the kill line's inability to transmit pressure. Resolving this would require further investigation. It can be stated that it would be undesirable for this diluted, unstable fluid to enter the kill line during the negative-pressure test.
- The polymer content of the blend material may have decreased the permeability of any settled material and potentially the ability to transfer pressure.
- The uniformity of the blend of seawater and spacer for the tests was achieved with a Hamilton-Beach mixer without the introduction of excessive shear. This likely achieved better blending than in the field, and as a consequence, it is less likely that it represented the actual severity of the settlement.

Dehydration of the spacer by applied differential pressure

- FORM-A-SQUEEZE, which was part of the spacer, is designed to lose all associated fluid under differential pressure and to form a cake of solids to cure lost circulation. Testing showed that when this fluid was blended with FORM-A-SET™, this type of behavior no longer existed. However, the mixtures of FORM-A-SET™ AK and FORM-A-SQUEEZE did rapidly develop impermeable filter cakes in an American Petroleum Institute filter press. While it is not thought that dehydration by applied pressure directly led to solids blocking the kill line, it could have been contributory.

6. Analyze mud samples received from M/V *Damon Bankston* to establish if deck samples are SOBM.

- Gas chromatography showed that the base fluid content of both deck samples was very similar to the analysis of the base fluid from the SOBM and could be assumed to be SOBM. It appeared that there were no peaks in the chromatograph that would be indicative of hydrocarbons from the well.
- Analysis of the solids extracted from the sample labelled 'bulk mud deck' indicated that it was SOBM.
- Analysis of the solids extracted from the sample labelled 'liquid mud deck' indicated the presence of SOBM, but there is other material there, particularly calcite.

7. Establish how much drilling fluid had been offloaded from the rig to M/V *Damon Bankston* and how much drilling fluid was still on the rig.

- The fluids-specific study team performed no work on this area. It was carried out by other members of the investigation team.

8. Identify if there was a visible difference between the SOBM and the spacer used in the well, and establish (if possible) what was coming out of the well at the time leading up to and during the evacuation.

- There was a color difference between the SOBM and the spacer used in the well, but detection would have relied on strokes or on following electrical stability meter trends.
- With the probable stringing out of the spacer in the well, it is likely that a mixture of spacer and seawater could have still been returning from the well. This is not known, as returns were overboard at this stage.
- The M-I SWACO compliance engineer passed the returns during the static sheen test as suitable for displacement, which would indicate minimal SOBM in the returns. An additional 265 bbls (which was diverted overboard) was reported as pumped prior to loss of real-time data. Evidence given by the M-I SWACO compliance engineer at the May 28, 2010, MBI hearings did not indicate any unusual properties in the returning spacer.

Other findings: Cross–linking of the spacer

- It was not possible to cross-link the most likely spacer blend (62/38 vol/vol FORM-A-SET™ to FORM-A-SQUEEZE at 45°F) with the cross-linker/activator designed by M-I SWACO for that purpose. The 54/46 vol/vol blend did show significant cross-linking within an hour of the addition of the activator. This may be explained by the higher dilution of retarder caused by the greater quantity of FORM-A-SQUEEZE in the final 54/46 vol/vol blend.
- No other materials were tested for their ability to cross-link, given that the material designed for this purpose was the most likely to achieve the purpose. The investigation team does not believe that this was a cause of the blockage for the following reasons:
  - M-I SWACO, in the information it provided to the investigation team, stated that the cross-linking agent was not added.
  - After weighting-up the spacer on the surface, it sat for 11 1/4 hours prior to pumping with no reported change in properties.
  - Once the fluid was cross-linked, it would have been visually obvious. There were no reports from the crew present at the shale shakers of any of this material returning.
  - Although it is unlikely that the fluid was cross-linked, the work in this area was not definitive.