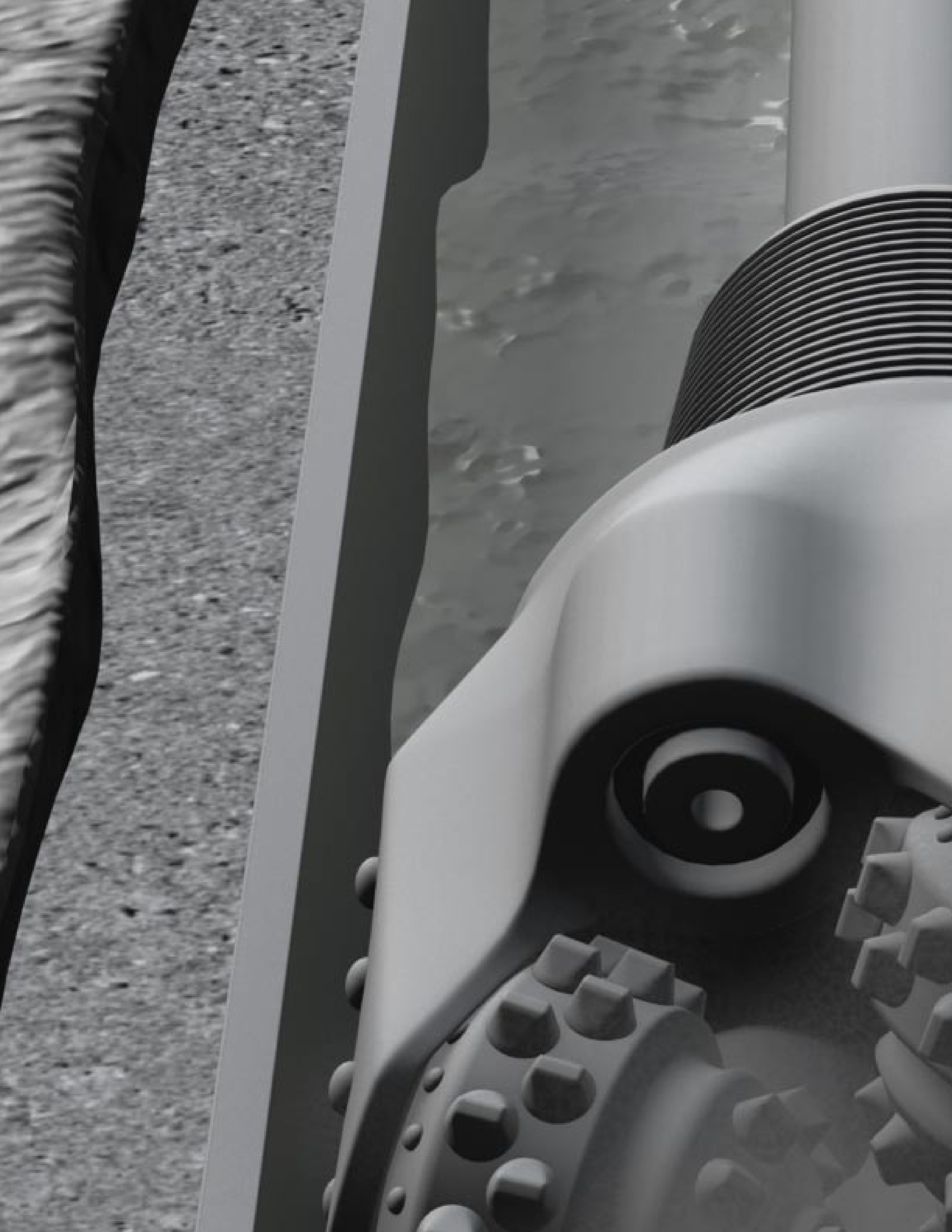


Chapter 4.4 | Foamed Cement Stability

BP and Halliburton chose to cement the final Macondo production casing into place using nitrogen foamed cement. That technology offered several advantages at Macondo, but it also posed a risk: An improperly designed or incorrectly pumped nitrogen foamed cement slurry can be unstable and lead to a failed primary cement job. Data from pre- and post-job laboratory testing lead the Chief Counsel's team to conclude that the foamed cement slurry pumped at Macondo was very likely unstable. The Chief Counsel's team finds that Halliburton failed to review properly the results of its own pre-job tests, and that a proper review would have led Halliburton to redesign the cement slurry system. The Chief Counsel's team also finds that BP inadequately supervised the cement design and testing process.

Foamed Cement

Cementing personnel create **nitrogen foamed cement** by injecting inert nitrogen gas into a base cement slurry. This produces a slurry that contains fine nitrogen bubbles. If the system is properly designed, the bubbles will remain evenly dispersed in the slurry as it cures, and the set cement will retain the bubbles in the same form.

Foamed cement offers two principal technical advantages. First, the nitrogen bubbles in the foamed cement slurry make the overall cement mixture less dense than the base cement slurry. Second, cementing personnel can adjust the density of the foamed cement slurry in response to well conditions by adjusting the rate at which they inject the nitrogen into the base cement slurry. Whereas a base cement slurry typically weighs about 15 pounds per gallon (ppg), foamed cement can weigh as little as 5 ppg.[1] All other things being equal, a low-density column of cement in the annular space around a well casing will exert less hydrostatic pressure on the formation than a high-density column of cement. As a result, using a low-density foamed cement can reduce the risk of formation breakdown. Such a breakdown may result in the loss of cement into the formation, compromising zonal isolation and reducing the productivity of the well over the long term.[2]

Risks of Unstable Foamed Cement

A foamed cement system must exhibit good foam **stability**.[3] A stable nitrogen foamed cement slurry will retain the nitrogen bubbles internally and maintain its design density as the cement cures. The result is hardened set cement that has tiny, evenly dispersed, and unconnected nitrogen bubbles throughout. If the foam does not remain stable as the cement cures, the small nitrogen bubbles may coalesce into larger ones, potentially rendering the hardened cement porous and permeable to fluids and gases, including hydrocarbons.[4] If the instability is particularly severe, the nitrogen can **break out** of the cement, with unpredictable consequences.[5] While technical authorities do not appear to have definitively determined the effects of pumping unstable foamed cement downhole, they uniformly agree that only stable foamed cement designs should be used.[6]

Foamed Cement Testing

When designing a nitrogen foamed cement system, it is critical to test the stability of the foamed slurry.[7] The American Petroleum Institute (API) has published recommended procedures for conducting **foam stability tests**.[8] The technician mixes a volume of base cement slurry with air (not nitrogen) in a sealed blender to generate a foamed slurry of the same density that will be used in the field (see Figure 4.4.1). The laboratory may then conduct foam stability tests using one of two methods.

Figure 4.4.1. Foam testing apparatus.

Five-blade blender.

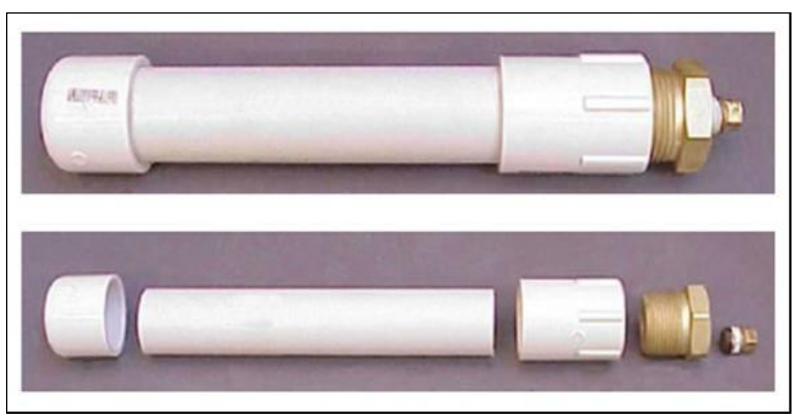
API RP 10b-4

The first method involves pouring a sample of the foamed cement into a graduated cylinder (see Figure 4.4.2). After two hours, the technician visually examines the foamed slurry for signs of instability, such as large coalescing bubbles or cement density variations caused by nitrogen bubble migration or escape.

The second method involves pouring the foamed cement into a plastic cylinder, sealing it, and then allowing it to cure and set (see Figure 4.4.3). The technician then removes the solid cement sample from the cylinder and measures the density of solid cement at the top, middle, and bottom of the sample. If there are density variations from top to bottom, or if the densities are equal to one another but significantly higher than the target density, the foamed cement is deemed unstable.

Figures 4.4.2 and 4.4.3. Foam testing apparatus.

Sambhav N. Sankar



API RP 10b-4

Left: Graduated cylinder for unset foam test.
Above: Curing mold for set cement tests.

The API lists five signs of foamed slurry instability in the laboratory:[9]

- more than a trace of free fluid;
- bubble breakout noted by large bubbles on the top of the sample;
- excessive gap at the top of the specimen;
- visual signs of density segregation as indicated by streaking or light to dark color change from top to bottom; and
- large variations in density from sample top to bottom.

None of these criteria is quantitative. All rely to some degree on the judgment of laboratory personnel or cementing experts.

Foamed Cement at Macondo

Decision to Use Foamed Cement

BP and Halliburton planned from the very beginning to use foamed cement technology for at least some of the cementing work at Macondo. It is common to use foamed cement on the first few casing strings in a deepwater well because shallow formations are often too weak to withstand the hydrostatic and dynamic pumping forces exerted by a heavier, normal-density cement slurry. (The *Marianas* crew and Halliburton cemented at least two of Macondo's early casing strings with foamed cement.)[10]

Operators use foamed cement less frequently for deeper casing strings and in applications for which synthetic oil-based mud is being used as a drilling fluid. While at least one operator—Shell—often uses foamed cement in deepwater Gulf of Mexico production casings, BP appears to have had relatively little experience with using the technology for this purpose.[11]

To cement the final long string production casing at Macondo, Halliburton and BP began planning as early as February 2010 to start with a base slurry having a density of 16.7 ppg and then to add enough nitrogen to reduce the density to 14.5 ppg. It appears that BP drilling engineer Brian Morel first raised the idea of using foamed cement technology for the production casing. He suggested the idea because using foamed cement might provide long-term strength benefits over the life of the well.[12] Halliburton cementing engineer Jesse Gagliano agreed that foamed cement would be useful at Macondo.[13] But an internal BP cementing expert cautioned Morel as early as March 8 that:

> Foaming cement after swapping to [oil-based drilling mud] presents some significant stability challenges for foam, as the base oil in the mud destabilizes most foaming surfactants and will result in N_2 [nitrogen] breakout if contamination occurs. This drives the need for a lot of attention to the spacer programs and often results in non-foamed cap slurries being placed on top of the foamed slurry to mitigate breakout.[14]

The early April lost returns problems appear to have further solidified the decision to use nitrogen foamed cement. According to BP and Halliburton's calculations, using the lighter foamed cement would reduce the risk of fracturing the formation at the well and thereby reduce the risk of losing returns during the cementing process.

Pre-Blowout Cement Testing

When the *Deepwater Horizon* arrived at Macondo to replace the *Marianas*, it had on board a large quantity of cement dry blend that Halliburton had originally designed for use at Kodiak #2, the previous BP well the *Horizon* crew had drilled.[15] Gagliano had designed the primary features of that blend in late 2009.[16]

Dry Blend. The term **dry blend** refers to the combination of dry cement components that are blended together onshore for use on the rig. The Macondo dry blend included Portland cement, two different grades of silica powder, potassium chloride, a proprietary antisettling agent, and a proprietary flow-enhancing additive. The rig cementing team added water, two liquid chemical additives, and a glass fiber material to the dry blend to produce the base slurry.

On February 10, Gagliano instructed technicians in Halliburton's Broussard, Louisiana, laboratory to conduct pilot tests on a cement slurry recipe based on this dry blend. The slurry recipe specified the amount of water and the type and quantity of liquid chemical additives that should be mixed with the dry blend to produce the cement slurry. If the dry blend had been unsuitable—either because of its original design or because it had degraded during storage—then Halliburton could have delivered a new dry blend to the rig for use at Macondo.

Foamed Cement Pilot Testing

Gagliano's February 10 pilot cement design listed the precise amount of liquid retarder, surfactant, and fresh water that the laboratory should add to the dry blend to produce a cement slurry for testing. The "recipe" that Halliburton tested in February was identical to the recipe that it eventually used at Macondo, with one exception: The February recipe included roughly twice the amount of liquid chemical "retarder" that Halliburton eventually used (0.20 gallons per sack (gal/sack) vs. the final 0.09 gal/sack) and correspondingly less water. (Adding retarder extends the setting time of cement.)[17] The laboratory used the dry blend from the *Deepwater Horizon* but used local tap water and stock liquid chemicals rather than water and liquid chemicals from the rig.

The Broussard laboratory conducted several tests in February, including two separate foam stability tests.[18] Both foam stability tests were "set" slurry tests, in which personnel poured foamed cement into a cylinder, allowed it to cure for 48 hours, and then examined the density of the top and bottom of the set cement cylinder.

Laboratory personnel appear to have conducted the first February foam stability test on or about February 13. The top and bottom of this sample weighed 16.8 ppg and 17.6 ppg, respectively. These measurements indicated serious instability because they differ significantly from each other, and they are both higher than the target density of 14.5 ppg. *The test measurements showed either that: (1) The lab personnel were unable to generate a proper foamed slurry; (2) gas bubbles migrated within the foamed slurry; (3) gas escaped from the slurry before it could set; or (4) some combination of these things occurred.*

Laboratory personnel appear to have conducted a second February foam stability test on or about February 17. The top and bottom of this sample weighed 15.9 ppg and 15.9 ppg, respectively.

While these two measurements were identical, the data still indicated serious instability because both measurements were significantly higher than the target density of 14.5 ppg. Again, nitrogen gas must have escaped from the tested slurry before it could cure, or the lab personnel had been unable to generate a proper foamed slurry.

These two February 2010 lab tests should have caused Halliburton technical personnel to conclude that the foamed cement Halliburton was planning to pump at Macondo was likely unstable.

Three other facts about the February tests are worth noting. First, laboratory personnel did not condition the cement before conducting the February 13 foam stability test but conditioned the cement for two hours before conducting the February 17 test. Second, rheology test results showed that the yield point of the base slurry was quite low. This can be an independent warning that the base slurry may be unstable and that a foamed slurry prepared from that base slurry may also be unstable.[19] Third, time-lapse strength testing showed that the pilot cement recipe set extremely slowly, suggesting that the recipe included too much retarder.

Halliburton did not report any of the February pilot testing data to BP until March 8.[20] On that date, Gagliano attached an official data report of the February test results to an email in which he discussed his recommended plan for cementing one of the Macondo casing strings.

The official data report included only the results of the February 17 foam stability test, in which the top and bottom portions of the set cement both weighed 15.9 ppg. (The official laboratory reports list the results in terms of specific gravity (SG) rather than pounds per gallon.) Because the top and bottom weights matched, the test did not demonstrate density segregation, but the test was still a clear failure because both weights were significantly higher than the target density.

For some unexplained reason, Halliburton's official data report to BP *incorrectly* stated that laboratory personnel had not conditioned the cement prior to the February 17 foam stability test.

Apparently, Halliburton did no further testing of the proposed Macondo cement slurry until April 2010, as the final production casing planning was under way.

April 13 Pre-Job Testing

On April 1, Morel sent an email to Gagliano, BP senior drilling engineer Mark Hafle, BP operations engineer Brett Cocales, and Quang Nguyen of Halliburton requesting that Halliburton begin testing cement for the final production casing cement job. Morel wrote, "This is an important job and we need to have the data well in advance to make the correct decisions on this job."[21] Gagliano responded on the same day with an email stating that he had already run the February pilot tests, and that he would run further tests "[o]nce I get samples from the rig sent into the lab" and once he had the latest data on the downhole temperatures at the well.[22] Gagliano attached the same official laboratory report that he had sent on March 8.

Gagliano appears to have first ordered additional testing on April 12.[23] This time, the laboratory tested samples of dry blend, additives, and water from the rig, and used a design recipe that was nearly identical to the one that Halliburton eventually pumped. (The tested recipe contained slightly less retarder than the pumped recipe—0.08 gal/sack instead of 0.09 gal/sack.) According to Gagliano, the main goal of this test was to determine how much retarder the recipe should use.[24]

It appears that the laboratory performed a foam stability test on this recipe on or about April 13 and conditioned the cement slurry for 1.5 hours at 180 degrees before conducting the test.[25] They finished the test on or about April 15. After curing, the top and bottom of the set cement sample weighed 15.7 ppg and 15.1 ppg, respectively.

This April 13 test result, just a week before the blowout, indicated serious instability.[26]

On April 17, Gagliano sent an email to Morel, Cocales, and BP drilling engineer team leader Gregg Walz and attached two official laboratory reports.[27] The data reports included results from various tests on cement slurry recipes with two slightly different retarder concentrations: 0.08 gal/sack and 0.09 gal/sack. BP and Halliburton had discussed increasing the retarder concentration in order to compensate for the fact that they planned to pump the cement at a low rate. The slow pumping rate would translate to increased cement travel time, which would in turn raise the risk of premature cement thickening.

Neither data report included the results of the April 13 foam stability test (or any other foam stability test). *Gagliano did not otherwise alert BP to the foam stability test results*. Gagliano's cover email discussed the data from recently completed thickening time tests, presumably because this measured the cement characteristic that would vary depending on retarder concentration. Gagliano also stated that he had not yet obtained compressive strength results for the final cement recipe that BP planned to use—which included slightly more retarder.

Morel complained to Hafle that Gagliano had started the compressive strength tests later than he should have. Morel asked Hafle if Morel would be "out of line" by sending the following message to BP wells team leader John Guide and Walz:

> I need help next week dealing with Jesse. I asked for these lab tests to be completed multiple times early last week and Jesse still waited until the last minute as he has done throughout this well. This doesn't give us enough time to tweak the slurry to meet our needs.... As a team we requested that [Gagliano] run another test with 9 gals on Wednesday, I know the first [compressive strength] test had issues, but I do not understand what took so long to get it underway and why a new one wasn't put on right away. There is no excuse for this as the cement and chemicals we are running has been on location for weeks.[28]

Hafle agreed that Morel's concerns were reasonable and that BP should ask Halliburton to replace Gagliano soon (a request that BP appears to have made earlier as well).[29] Morel and Hafle conveyed their concerns to Walz, Cocales, and Guide, and on April 18, Walz responded that he and Guide would be meeting soon with Halliburton.[30]

Meanwhile, on April 17, Morel responded directly to Gagliano's email. Morel wrote:

> I would prefer the extra pump time with the added risk of having issues with the nitrogen. What are your thoughts? There isn't a compressive strength development yet, so it's hard to ensure we will get what we need until it[']s done.[31]

Morel thus told Gagliano that he would prefer to alter the cement slurry recipe to include more retarder to increase the thickening time (or "pump time") of the cement. In the same email, he appears to have recognized that adding more retarder would potentially increase the risk of nitrogen foam instability.

Laboratory personnel appear to have conducted a second April foam stability test on or about April 18.[32] They used the same amount of retarder (0.08 gal/sack) but conditioned the cement at 180 degrees for three hours—the longest period yet. The top and bottom of the set cement sample weighed 15.0 ppg and 15.0 ppg, respectively.

While these numbers are the same as each other, they are both 0.5 ppg higher than the target of 14.5 ppg. This means one of two things. First, laboratory personnel may have generated a foamed cement slurry that *initially* weighed 15.0 ppg and retained that density throughout the test. If this was the case, however, the laboratory documents should at least have noted the difficulty; API standards state that if laboratory procedures generate a foamed slurry density that is above the design density, "it will be difficult to obtain the proper foamed cement density in the field, and the slurry should be redesigned."[33]

Second, laboratory personnel may have generated a foamed slurry of 14.5 ppg, but some nitrogen gas may have escaped from the slurry as it set, making the slurry more dense. Because the change from 14.5 to 15.0 ppg is not indisputably "large" within the meaning of API testing criteria, this might suggest that the foamed cement was stable. Halliburton appears to contend that this is what happened and argues that the April 18 test shows that its cement slurry was stable.

Internal documents provided by Halliburton do not clarify which of these two things happened.

Availability of April 18 Test Results

The documents also do not establish conclusively *when* Halliburton completed its April 18 foam stability testing. Handwritten notes in the documents suggest that laboratory personnel began the test at 2:15 a.m. on April 18,[34] and Halliburton has confirmed this time in correspondence to the Chief Counsel.[35] Halliburton at one point stated publicly that the test took 48 hours to complete.[36] If that were true, the test results would not have been complete until at least 2:15 a.m. on April 20, which would have been after the time Transocean's rig crew and Halliburton's cementing personnel *finished* pumping the primary cement job at 12:35 a.m. on April 20.[37]

Six months after the blowout, and after the Chief Counsel's team publicly questioned the stability of the Macondo cement design and the timing of lab testing, Halliburton still had not determined whether its personnel had completed the April 18 foam stability test before pumping the Macondo job.[38] Finally, eight months after the blowout, Halliburton informed the Chief Counsel that it had "learned more about the specific facts surrounding the cement lab testing," including that "the second April foam stability test was finished before the final cement job started."[39] In the words of its counsel:

> Halliburton can now demonstrate that an email notification was sent to Jesse Gagliano on April 19, 2010, at approximately 4:14 pm indicating that all tests associated with the final cement job were then "finished in lab," more than three hours before the cement job commenced. Attached to this letter is a copy of a spreadsheet containing the "web log" data referenced above and explained further in Halliburton's January 7th letter to you. This constitutes objective evidence…that the foam stability test was run in less than 48 hours and that the test was completed prior to the final cement job.[40]

Halliburton contended that the "finished" notification "would not have been generated had the foam stability test failed or been incomplete."[41]

The Chief Counsel's team cannot accept or reject Halliburton's contentions based on these statements by its counsel. While Halliburton did provide a one-page spreadsheet that it views as "objective evidence" of the timing of its test, the Chief Counsel's team cannot decipher the document (displayed as Figure 4.4.4) without the aid of Halliburton personnel.

Halliburton flatly refused to produce any witness who could explain this document (or any of the other timing and testing issues discussed above) in a transcribed interview.

Figure 4.4.4. Halliburton evidence of test times.

IP Address	UserID	Time Stamp	Web Server Log Information
		18.04.2010 09:52:03	From: noreply@halliburton.com; To: jesse.gagliano@halliburton.com; Subject of Email: Daily Summary Report
34.34.133.22	HBAM242	2010-04-18 20:44:50	GET /pls/viking/labdb_report.stepTwo?p_trid=73909 HTTP/1.1
34.34.133.22	HBAM242	2010-04-18 20:44:58	GET /pls/viking/labdb_report.stepThree?p_trid=73909&p_tsid=151852 HTTP/1.1
34.34.133.23	-	2010-04-19 02:49:26	GET /osso_login_success?urlc=v1.4~5E653963CE68A4ED43251CE43A205D9B7086D803CCD13504E93F7EDF2732CFF6B5E3D3C3D127BCED52C25007DEE121C4867F0A323F67857B2 056890280CDFC276BB16694F32B2E517C34927EE5F3421FAE4DDD7B19F9A62217A75D98E86E0458774B5442DEACD45A94060FC6F84ED7CA753A3110216F883F68CCC6E1DCD 36A7D7EE6EA99B9941A2F46D0A007F83612A1C80AF89CF3E1CD36079B34349877C6EF0801CA307D846FD6B91BB7BD9D93CCD005E52554B7B66A7D354B877ED5A7C45D824A 2D7584E66100764AE13369CB2D5E9B0324C30262DDA8A5ED681B9F2771A64FE5C0F1DD6ADC47C0C73E9508698E6A779C20B90D5626F110209015A07D32D95E542D4971949 FD79B82645EA26D68BC1B73F1E4528ACE1558AC30B311F1619B3CA6025ACF3EAD1D0B10747619CAF240468D01B991ECB5CB14C3E93EE3C484795C6DA60084EF081A661C18F DF8C195B21FEA9DCD749C07D3CFD43C29A9165898D409359D739095C534F3CAB83DBBF84D HTTP/1.1
		19.04.2010 09:52:08	From: noreply@halliburton.com; To: jesse.gagliano@halliburton.com; Subject of Email: Daily Summary Report
		19.04.2010 16:04:13	From: noreply@halliburton.com; To: jesse.gagliano@halliburton.com; Subject of Email: Test Status Changed (US-73909/2)
34.34.133.23	HX11269	2010-04-19 16:13:27	GET /pls/viking/labdb_test.testresults?p_request_id=73909&p_slurry_id=150924&p_test_id=43&p_request_test_id=806072 HTTP/1.1
34.34.133.23	HX11269	2010-04-19 16:13:28	GET /pls/viking/labdb_test.testresults?p_request_id=73909&p_slurry_id=150924&p_test_id=43&p_request_test_id=813603 HTTP/1.1
34.34.133.23	HX11269	2010-04-19 16:14:25	GET /pls/viking/labdb_test.testresults?p_request_id=73909&p_slurry_id=150924&p_test_id=43&p_request_test_id=813603&p_message=Results%20successfully%20updated HTTP/1.1
34.34.133.23	HX11269	2010-04-19 16:14:32	GET /pls/viking/labdb_test.testresults?p_request_id=73909&p_slurry_id=150924&p_test_id=43&p_request_test_id=806072 HTTP/1.1
34.34.133.23	HX11269	2010-04-19 16:14:33	GET /pls/viking/labdb_test.testresults?p_request_id=73909&p_slurry_id=150924&p_test_id=43&p_request_test_id=813603 HTTP/1.1
		19.04.2010 16:14:43	From: noreply@halliburton.com; To: jesse.gagliano@halliburton.com; Subject of Email: Request 73909, Status: Finished in Lab
34.34.133.23	HX11269	2010-04-19 16:14:46	GET /pls/viking/labdb_test.testresults?p_request_id=73909&p_slurry_id=150924&p_test_id=43&p_request_test_id=813603 HTTP/1.1
34.34.133.23	HX11269	2010-04-19 16:14:47	GET /pls/viking/labdb_test.testresults?p_request_id=73909&p_slurry_id=150924&p_test_id=43&p_request_test_id=806072 HTTP/1.1
34.34.133.22	HX46076	2010-04-20 08:36:37	GET /pls/viking/labdb_test.testresults?p_request_id=73909&p_slurry_id=150924&p_test_id=43&p_request_test_id=806072 HTTP/1.1
34.34.133.23	HX46076	2010-04-20 08:36:37	GET /pls/viking/labdb_test.testresults?p_request_id=73909&p_slurry_id=150924&p_test_id=43&p_request_test_id=813603 HTTP/1.1
		20.04.2010 09:52:11	From: noreply@halliburton.com; To: jesse.gagliano@halliburton.com; Subject of Email: Daily Summary Report
34.34.133.22	-	2010-04-20 11:31:10	GET /osso_login_success?urlc=v1.4~78AECBB7DF3421DD9F6E1C845ED7C386DE726BE1B2FEFD0F1D9669DB7EED49633BB73DB640D6B484F56E44FA456B225B05EDFA2F96C9E574 6825AB490FE2BC191E21939751490E4610FC302D5388AB16E487526D7CEBDFDCD3D36256E14B7BD9941406DB3169C961B56D01AAEEC3A0B77054D1B9CD7739644856C67DE 5FF4C6CD6A9C4E50A10E61076E13624C863709003F5A1CFA9C4F6E6B7ADA26F7F2137EB8639F3710D5E4B13A60D60B4F55E5472F673D6D0516F206C34815F3337CC9F1F4823 17526A47ED03BC5CD212B71B24A511513D26C63F2A697CD02682641532D96BFE33AAD34BA87A71395D802D528FF058447F4BDEC0C66E9BCA2CA64893EE4CF3E2FE2FC7B82 B9A49CA1FF6B0A2C354851DF5729CB6A0E31CE58E2837390911D8F9EE1E1645D331D7403CD66B04F38A6ED5B251AE849E0C5CE19E0FA6F7DCBBC9B429F477A6BC7557574C6 D20503333D5E9759002670D43DAB9B479C6BC6DA91D3F03065B3B5119 HTTP/1.1

Halliburton

Significant problems remain even if the Chief Counsel's team accepts Halliburton's assertions about when the April 18 test had been completed. While Halliburton argues that its computer system generated a notice that the April 18 test results were available before its personnel pumped the cement job, it has carefully avoided saying that any of its engineers actually *knew* that the results were available, let alone *reviewed* them, before pumping the job. Indeed, BP documents show that Halliburton first reported the April 18 result to BP on April 26, six days after the blowout.[42] And while Halliburton contends that the "finished" notification meant that the April 18 foam stability test did not fail by its standards, it refuses to identify those standards, let alone the person who actually applied them.

Halliburton presumably would not deny this information to the Chief Counsel if it were favorable to the company.

Post-Blowout Cement Testing

Testing by BP

BP's internal investigation raised several questions about Halliburton's cement slurry design and pre-job testing procedures.[43] BP asserted that the final April 18 foam stability test "indicated foam instability based on the foamed cement weight of 15 ppg."[44]

BP also commissioned third-party testing by CSI Laboratories, an independent cement consulting company.[45] CSI could not conduct these tests on the actual materials that had been used at the Macondo well because those materials sank into the ocean with the rig.

CSI also could not conduct these tests using the precise off-the-shelf ingredients specified by the cement slurry recipe because Halliburton refused to provide its proprietary additives to CSI. CSI therefore developed a model slurry to mimic the characteristics of the slurry used at Macondo. CSI prepared the model slurry by mixing commercially available cement and additives according to the final Macondo cement recipe. To replace proprietary Halliburton additives, CSI used third-party chemicals that served similar purposes (for example, using a commercially available third-party retarder instead of Halliburton's proprietary SCR-1000 retarder). Despite these differences, BP's investigation team asserted that the model slurry was "sufficiently similar to support certain conclusions concerning the slurries actually used in the Macondo well."[46]

CSI reported that foamed cement generated from the model slurry was unstable under several test conditions. Based in large part on this analysis, BP's investigation team concluded in its report that "the nitrified foamed cement slurry used in the Macondo well probably experienced nitrogen breakout, nitrogen migration and incorrect cement density."[47]

Testing by Chevron and Chief Counsel's Team

The Chief Counsel's team conducted its own independent tests of cement slurry stability on behalf of the Commission.

The Chief Counsel's team worked with an independent expert and cement experts from Chevron to conduct these tests.[48] Halliburton recognized that Chevron's laboratory personnel were highly qualified for this work; Chevron maintains a state-of-the-art cement testing facility in Houston, Texas, and employs a staff of cement experts to supervise cement design and testing for its oil wells. Halliburton also agreed to supply the Chief Counsel's team with off-the-shelf cement and additive materials of the same kind used at the Macondo well. Although these materials did not come from the specific batches used at the Macondo well, they are in all other ways identical in composition to the slurry pumped there.

Halliburton refused to provide the Chief Counsel's team with full details of the methods and protocols that its laboratory used to conduct its February and April cement tests. *Most notably, Halliburton refused to provide any information on whether and how its staff had conditioned the cement before conducting the foam stability tests.* (At the time Chevron conducted its tests, Halliburton had not yet produced any internal laboratory documents to the Commission staff. Halliburton later provided some internal documents that disclosed conditioning times.) When the Chief Counsel's team sought input from BP and other parties regarding these and other issues, Halliburton demanded that the team refrain from doing so.[49] The Chief Counsel's team agreed to honor Halliburton's request by working solely with Chevron experts and an independent expert to develop protocols for testing Halliburton's cement materials.

Chevron conducted numerous tests on the Commission's behalf. Chevron's laboratory report states that many of its results "were in reasonable agreement" with results reported by Halliburton. However, Chevron's staff did not obtain foam stability test results that agreed with Halliburton's. Instead, Chevron's report stated that its staff was "unable to generate stable foam with any of the tests" that they conducted to examine foam stability.[50] Chevron's testing strongly suggests that the foamed cement slurry actually used at Macondo was unstable. Appendix D is Chevron's letter to the Chief Counsel's team that accompanied its report.

Technical Findings

The Foamed Cement Slurry Used at Macondo Was Very Likely Unstable

Of all the tests done so far to evaluate the stability of the Macondo foamed cement slurry design, only one (the April 18 Halliburton pre-job test) even arguably suggests that the design would be stable.

Even the April 18 test result predicts only borderline stability. Industry experts believe that the three-hour high-temperature conditioning regimen for this test biased it in favor of success. Several have stated that cement laboratories should not condition a slurry sample *at all* before running foam stability tests, let alone at such elevated temperatures.[51] They reason that during field cementing operations, crews do not usually mix or circulate the base slurry before foaming it with nitrogen. Halliburton explained that its laboratory personnel derived the conditioning time from pumping time,[52] and then contended in writing that there is "sound operational basis" for conditioning cement in a laboratory prior to foam stability testing.[53] But when the Chief Counsel's team asked Halliburton to provide "[a]ny scientific study or other document" supporting the latter statement,[54] Halliburton cited only one thing: API Recommended Practice 10b-2.[55] Section 15 of that document states, "The cement slurry is conditioned to simulate dynamic placement in a wellbore." But this document discusses methods for testing the static stability of *unfoamed* cement slurries. By contrast, API's practice recommendations for testing *foamed* cement do not mention pre-test conditioning at all.

Halliburton also declined to provide any information that would help the Chief Counsel's team determine whether lab personnel had difficulty generating a proper density foamed slurry sample on April 18, which might account for the 15.0 ppg density of that sample.

Indeed, Halliburton repeatedly flatly refused Chief Counsel's personal requests for documents or recorded testimony regarding many otherwise unsupported assertions from Halliburton's lawyers. For example, Halliburton's lawyers have consistently asserted that the April 18 foam stability test produced passing results. Commission staff requested "any document specifying or prescribing the conditioning time…test duration, or success criteria" for this and other tests, and requested the opportunity to conduct and transcribe interviews with Gagliano, his supervisors, and any "individual or individuals competent to testify regarding standard Halliburton laboratory practices."[56] Halliburton produced no documents and provided no witnesses. It noted that it had allowed the Chief Counsel to interview Gagliano and a Halliburton cement expert early in the investigation—*before* the Chief Counsel had learned of the failed February and April tests and *before* the Chief Counsel's testing had identified concerns with the Macondo cement slurry recipe. Halliburton then stated:

> [H]alliburton is compelled to view these requested "interviews" as being more in the nature of adversarial depositions designed to defend the [Chief Counsel's] preliminary conclusions as opposed to furthering an objective evaluation of what occurred. Given Staff's apparent shift in purpose, Halliburton respectfully declines to make such witnesses available.

In contrast to the April 18 test, 12 other stability tests—three by Halliburton and nine by Chevron—clearly predict that the foamed cement slurry design would be unstable. One can debate the significance of these tests individually. For instance, the February Halliburton tests predicted severe instability but were performed with a recipe containing more retarder, which can potentially reduce slurry viscosity and make it more unstable.[57] And one can also debate how well laboratory testing approximates field conditions.[58] However, the sheer number of failed foam stability tests combined with other indicia of instability (discussed below) lead the Chief Counsel's team to conclude that the foamed cement slurry used at Macondo was very likely unstable.

The Commission-sponsored tests further suggest that the Halliburton base slurry was unstable even *before* being foamed with nitrogen. Chevron's lab report notes that its personnel observed base slurry "settling" in six of the nine tests it performed. The base slurry also consistently showed a very low yield point, which can be a warning that the slurry will be unstable before and after foaming. Base slurry instability also could have severely compromised the bottomhole cement job at Macondo.

The Chief Counsel's team notes that Halliburton's Broussard laboratory did retain a small sample (1.5 gallons) of dry blend material from the *Deepwater Horizon*. This material was left over from Halliburton's April pre-job testing process. At the time of this writing, the federal government had taken custody of the material and was holding it pending laboratory testing. Industry experts have informed the Chief Counsel's team, however, that the dry blend material has probably chemically degraded by now to the point where any laboratory testing results would be inconclusive. If this is the case, Halliburton's four pre-blowout tests and the Commission's nine post-blowout tests are the most probative information regarding the performance of the Macondo cement slurry.

Halliburton May Not Have Reviewed the April 18 Test Results Before Beginning the Cement Job

Currently available data lead the Chief Counsel's team to conclude that Halliburton did not fully review its April 18 foam stability tests before pumping the Macondo cement job. While Halliburton states that its personnel completed the test at approximately 4:14 p.m. on April 19, it has provided neither documentary nor testimonial evidence to show that its personnel actually reviewed that data before pumping the job or communicated it to anyone at BP.

Once again, the Chief Counsel repeatedly offered Halliburton opportunities to produce witnesses with relevant knowledge to be examined by the Chief Counsel. Halliburton consistently refused to support its lawyers' assertions with sworn testimony or additional documentation.

Even if Halliburton did review final test results before pumping the cement job, it did not transmit those results to BP until April 26—six days after the blowout.[59] On that date, Jesse Gagliano sent BP an official laboratory data report containing the results of the second April foam stability test. Halliburton never sent BP the results of the April 13 foam stability test.

Halliburton Should Have Redesigned the Slurry Before Pumping It

Halliburton personnel should have redesigned the Macondo slurry before pumping it. Richard Vargo, a Halliburton cementing expert who testified at the Commission's hearings on November

8, 2010, appears to agree. He testified: "I don't think at this point I would choose to run this slurry."[60]

Table 4.4.1 summarizes Halliburton's internal laboratory data concerning the stability of the Macondo cement slurry.

Table 4.4.1

Test ID	Apparent Date	Target Density in ppg	Top Density in ppg	Bottom Density in ppg	Retarder Concentration in gal/sack	Conditioning Time in Hours	Stable?	Available Before Job?	Sent to BP Before Job?
65112/1	Feb. 13	14.5	16.8	17.6	0.20	0:00	Unstable	Yes	No
65112/3	Feb. 17	14.5	15.9	15.9	0.20	2:00*	Unstable	Yes	Yes
73909/1	Apr. 13	14.5	15.7	15.1	0.08	1:30	Unstable	Yes	No
73909/1	Apr. 18	14.5	15.0	15.0	0.09	3:00	Arguable	Uncertain	No

* Reported to BP as 0:00

Halliburton personnel should have redesigned the cement slurry design after receiving the February pilot test results. Both of the February foam stability tests clearly indicated that the pilot cement design was severely unstable.

Halliburton has repeatedly argued that these pilot tests do not reliably predict the stability of the cement system used during the Macondo cement job. Specifically, Halliburton notes that the final cement design was different and that the final well conditions differed from BP and Halliburton's assumptions in February.[61]

These facts are irrelevant to the question of whether Halliburton should have redesigned its slurry. The pilot test results showed that Halliburton's then-current design would be unstable under BP's then-available predictions of well conditions.[62] This should have led Halliburton to inform BP of the problem and to redesign the slurry as necessary. Instead, the Chief Counsel's team has found nothing to suggest that Halliburton personnel seriously considered the issue.

Halliburton missed another clear warning in April. The April 13 foam stability test data should again have prompted Halliburton to inform BP of stability problems and to redesign the slurry immediately. Halliburton personnel have since testified that they would not use a slurry that generated such test results.[63]

Halliburton contends that its laboratory personnel conducted the April 13 test improperly and that the results are therefore "irrelevant."[64] Halliburton cites a laboratory document to support this conclusion, but the Chief Counsel's team and an independent cementing expert were unable to confirm the conclusion merely by reviewing that document. The Chief Counsel asked Halliburton to provide witness testimony to support this assertion, but Halliburton declined.

Even if Halliburton personnel did conduct the April 13 test improperly, this is again irrelevant to the question of whether Halliburton should have redesigned the slurry. As of April 15, the *only* data Halliburton had in hand predicted that the Macondo slurry design would be unstable, and Halliburton had very little time before it would have to pump the cement job. Under the circumstances, Halliburton should have immediately redesigned the slurry and immediately retested the new design. It appears that some Halliburton personnel recognized the problem and responded by rerunning the test two days later with additional conditioning time, perhaps hoping for a more favorable result. But that response was wholly inadequate given how soon the job was to be pumped and the fact that the April 13 test results were consistent with the two earlier February test results. On April 15 or shortly thereafter, Halliburton should have immediately alerted BP to the stability problem and immediately begun redesigning the Macondo slurry.

The Chief Counsel's team is not certain why Halliburton chose not to redesign its slurry. There are at least two possible explanations. One is that the Halliburton personnel who were responsible for approving or recommending the design were unaware of the foam stability test results or their importance. The other is that those personnel *were* aware of the results but did not consider them sufficiently problematic.[65]

Management Findings

Halliburton Mismanaged Its Cement Design and Slurry Testing Process

The number and magnitude of errors that Halliburton personnel made while developing the Macondo foamed cement slurry point to clear management problems at that company. In addition to the errors described above, the Chief Counsel's team believes that Halliburton personnel:

- began pumping the Macondo job without carefully reviewing laboratory foam stability data and without solid evidence that the foamed cement design would be stable;
- reported foam stability data to BP selectively, choosing in February not to report the more unfavorable February 13 test, and choosing in April not to report the more unfavorable April 15 test result (although Halliburton contends these results were erroneous);
- selected the pre-test conditioning time informally, choosing different conditioning times (ranging from no time to three hours) in each of the four foam stability tests without any stated explanation;
- assumed, without apparent scientific basis, that conditioning the base slurry before foaming was scientifically equivalent to foaming the cement then pumping it down the well; and
- recommended a cement design without conducting any formal internal review of that design. Notably, the only design element that Halliburton manipulated between February and April was retarder concentration, even though BP's well design changed significantly during that period and even though bottomhole well conditions were unknown in February. Halliburton has provided no evidence that a supervisor or senior technical expert ever reviewed the final cement slurry design.

To date, Halliburton has not provided any documents or testimony to suggest that established company rules or guidelines prohibited its personnel from doing any of these things. And if such guidelines did exist, it appears that Halliburton failed to enforce them on the Macondo job.

Halliburton's Lab Report Format Complicated Data Evaluation

Halliburton's lab reports to BP were highly technical. As with its modeling runs, discussed in Chapter 4.3, Halliburton did not provide a summary of results, an overall assessment of slurry design, or even reference values for any of the laboratory data it provided to BP. Halliburton could have improved the value of the reports by, for instance, inserting its criteria for a successful foam stability test alongside the reported foam stability data. This would not only have helped BP personnel understand the significance of relatively obscure numerical data, but might also have helped Halliburton personnel do so as well.

BP Did Not Adequately Supervise Halliburton's Work

BP technical guidance documents for cementing emphasize the importance of timely cement testing,[66] and BP Macondo team members themselves recognized that timely cement testing was important.[67] The team also expressed internal concern well before the blowout that Jesse Gagliano was not providing "quality work"[68] and was not "cutting it"[69] by waiting too long to start important tests. They had already asked Halliburton to reassign Gagliano, and Halliburton had apparently agreed to do so.[70] But while BP engineers discussed "how to handle Jesse's interim performance" by email on the very day of the blowout,[71] they did not double-check his work or supervise him more closely pending his replacement.

In particular, although BP personnel recognized the "significant stability challenges" of using foamed cement for the Macondo production casing,[72] and that changes to the retarder concentration in the cement design might increase the risks of foam instability,[73] BP does not appear to have insisted that Halliburton complete its foam stability tests—let alone report the results to BP for review—before ordering primary cementing to begin.[74] When asked why, a BP representative said, "I think we didn't appreciate the importance of the foam stability tests."[75]

BP also did not adequately supervise the slurry design process or review earlier test results.[76] BP documents show that its engineers questioned Gagliano's slurry recipes in other instances.[77] But the Chief Counsel's team found nothing to suggest that BP questioned the Macondo slurry recipe, even after the slurry failed to perform properly during the cement job for the 16-inch casing string. (A BP engineer explained that Halliburton dismissed the failure as the result of cement contamination and noted that this is a typical response for any cementing contractor.)[78] While the Macondo team consulted its in-house cementing expert on other issues, they did not ask him to review the foamed slurry recipe.[79] The expert raised several concerns as soon as he reviewed the recipe after the incident—among other things, he expressed surprise that the slurry design did not include a fluid loss additive and did include a defoamer additive.[80]

BP's failures are especially troubling because it had previously identified several relevant areas for concern during a 2007 audit of Halliburton's capabilities. In that year, BP hired Cemtech Consulting to review a Halliburton foamed cement job on the Na Kika project in the Gulf of Mexico.[81] Cemtech's report identified several issues that mirror problems at Macondo. For instance, Cemtech observed that Halliburton's initial foamed slurry design at Na Kika "had tendencies to stratify" (that is, was unstable) and required redesign. Cemtech also made broader observations such as:

- "The HES [Halliburton] Fluids Center chemists and senior lab technicians do a very good job of testing cement slurries, but they do not have a lot of experience evaluating data or assisting the engineer on ways to improve the cementing program."
- "COMMUNICATION and DATA TRANSFER/DOCUMENTATION could be improved to help avoid unnecessary delays or errors in the slurry design testing, data reporting, and evaluation of the cement program."
- "Lab reports could be improved! They are difficult to evaluate; often incomplete; and are submitted WITHOUT supporting lab charts and DATA to validate the test results. LAB DATA SHOULD BE MANDATORY!"

It does not appear that BP pressed Halliburton or its own Gulf of Mexico engineering teams to improve in these areas.