NATIONAL ACADEMY OF ENGINEERING *AND*
NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

November 16, 2010

The Honorable Kenneth L. Salazar
Secretary
U.S. Department of the Interior
1849 C Street, NW
Washington, DC 20240

Subject: Interim Report on Causes of the *Deepwater Horizon* Oil Rig Blowout and Ways to Prevent Such Events

Dear Mr. Secretary:

In response to your request, the National Academy of Engineering (NAE) and the National Research Council (NRC) formed a committee to examine the causes of the *Deepwater Horizon* mobile offshore drilling unit (MODU)–Macondo well blowout, explosion, fire, and oil spill that occurred on April 20, 2010, and to identify measures for preventing similar incidents in the future. The committee membership includes NAE members and other similarly qualified practitioners and academicians who bring a broad spectrum of expertise, including the areas of geophysics, petroleum engineering, marine systems, accident and incident investigations, safety systems, risk analysis, human factors, and organizational behavior (see Appendix A). This letter constitutes the interim letter report required in the committee's statement of task (see Appendix B).

To inform its deliberations, the committee obtained information from a variety of sources. It heard presentations from representatives of government and private organizations, observed hearings conducted by the Marine Board of Inquiry (MBI),[1] made site visits, and assessed written information (see Appendix C). At the time the committee completed its deliberations for this report, it had not been able to examine the blowout preventer (BOP) that was part of the drilling operation at the Macondo well nor to interview representatives of Cameron (manufacturer of the recovered BOP) or Transocean [owner and operator of the *Deepwater Horizon* mobile offshore drilling unit (MODU)]. Also, the committee only recently received requested technical drilling data, which are still being analyzed. Therefore, the committee's information-gathering activities and deliberations concerning the probable causes of the *Deepwater Horizon* incident will continue beyond this interim report.

[1] The MBI is being conducted by the U.S. Department of the Interior, Bureau of Ocean Energy Management, Regulation and Enforcement (BOEM), and the U.S. Coast Guard to develop conclusions and recommendations as they relate to the *Deepwater Horizon* mobile offshore drilling unit explosion and loss of life. Witness testimonies at MBI hearings are cited throughout this report. Testimony transcripts are posted on the internet. See http://www.deepwaterinvestigation.com/go/site/3043/.

The committee notes that, at this time, multiple theories and factors have been proffered with regard to the specific failure mechanism and hydrocarbon pathway that led to the blowout of the Macondo well. Most of the theories and factors have in common issues regarding the effectiveness of cementing the long-string production casing to prepare the well for temporary abandonment.

The committee further notes that it may not be possible to definitively establish the precise failure mechanism and hydrocarbon pathway that led to the blowout of the well, given the tragic loss of 11 witnesses, the sinking of the rig along with important operating records, and the general difficulty in obtaining reliable forensic information at the depth of the Macondo well. In addition, no information is available yet from the detailed examination of the recovered BOP. Nonetheless, in preparing this report, the committee believes it has been able to develop a good understanding of a number of key factors and decisions that may have contributed to the blowout of the well, including engineering, testing, and maintenance procedures; operational oversight; regulatory procedures; and personnel training and certification. It is important to note that the findings and observations in this interim report are preliminary and serve to identify areas of concern that will be pursued in greater detail in the final report. The committee will also consider government and private-sector initiatives recently developed for deepwater exploration in the United States. Therefore, the committee does not present recommendations at this time. As indicated in the committee's statement of task, this interim consensus report is provided to inform the ongoing activities of the MBI, the National Commission on the BP *Deepwater Horizon* Oil Spill and Offshore Drilling[2] and other formal investigations.

The committee's final report, due in June 2011, will present its overall findings regarding the causes of the *Deepwater Horizon* MODU explosion, fire, and oil spill and recommended approaches for minimizing the likelihood that similar events will occur in the future.

This interim report has been reviewed in draft form in accordance with procedures approved by the NRC Report Review Committee (see Appendix D for a list of reviewers). To permit adequate time for report preparation and review, information collected after October 1, 2010, was not considered for this report. The committee will continue to consider the issues discussed in this report as it carries out the remainder of its study.

I. SUMMARY OF PRELIMINARY FINDINGS AND OBSERVATIONS

On the basis of its assessment of the evidence collected for this interim report, the committee has developed the following preliminary findings and observations. The sequence in which they are presented is not intended to imply a sense of priority.

[2] The commission was established by President Obama to recommend ways of preventing and mitigating the impact of any future spills that result from offshore drilling. See http://www.oilspillcommission.gov/.

Additional discussion of each of these findings is presented later in subsequent sections of this report.[3]

1. The incident at the Macondo well and *Deepwater Horizon* MODU was precipitated by the decision to proceed to temporary abandonment of the exploratory well despite indications from several repeated tests of well integrity [the test type known as a negative (pressure) test] that the cementing processes following the installation of a long-string production casing failed to provide an effective barrier to hydrocarbon flow (Sections II and III).[4]

2. The impact of the decision to proceed to temporary abandonment was compounded by delays in recognizing that hydrocarbons were flowing into the well and riser and by a failure to take timely and aggressive well-control actions. Furthermore, failures and/or limitations of the BOP, when it was actuated, inhibited its effectiveness in controlling the well (Sections III and IV).

3. The failures and missed indications of hazard were not isolated events during the preparation of the Macondo well for temporary abandonment. Numerous decisions to proceed toward abandonment despite indications of hazard, such as the results of repeated negative-pressure tests, suggest an insufficient consideration of risk and a lack of operating discipline. The decisions also raise questions about the adequacy of operating knowledge on the part of key personnel. The net effect of these decisions was to reduce the available margins of safety that take into account complexities of the hydrocarbon reservoirs and well geology discovered through drilling and the subsequent changes in the execution of the well plan (Section VI).

4. Other decisions noted by the committee that may have contributed to the Macondo well accident are as follows:

    - Changing key supervisory personnel on the *Deepwater Horizon* MODU just prior to critical temporary abandonment procedures (Section VI);
    - Attempting to cement the multiple hydrocarbon and brine zones encountered in the deepest part of the well in a single operational step, despite the fact that these zones had markedly different fluid pressures (because of the different fluid pressures, there was only a small difference between the cement density needed to prevent inflow into the well from the high-pressure formations and the cement density at which an undesirable hydraulic fracture might be created in a low-pressure zone) (Section II);

[3] It was not feasible to provide substantial background information in this interim letter report. Therefore, readers are directed to primer sources, such as the following, for explanations of terms and concepts: *An Introduction To Marine Drilling* (2007) by Malcolm Maclachlan and *A Primer of Oilwell Drilling* (2008) by Paul Bommer.

[4] The section numbers refer to subsequent sections of this report.

- Choosing to use a long-string production casing in a deep, high-pressure well with multiple hydrocarbon zones instead of using a cement liner over the uncased section of the well (Section II);
- Deciding that only six centralizers would be needed to maintain an adequate annulus for cementing between the casing and the formation rock, even though modeling results suggested that many more centralizers would have been needed (Section II);
- Limiting bottoms-up circulation of drilling mud prior to cementing, which increased the possibility of cement contamination by debris in the well (Section II);
- Not running a bond log after cementing to assess cement integrity in the well, despite the anomalous results of repeated negative-pressure tests (Section II);
- Not incorporating a float shoe at the bottom of the casing as an additional barrier to hydrocarbon flow (Section II); and
- Proceeding with removal of drilling mud from the well without installing the lockdown sleeve on the production casing wellhead seals to ensure the seals could not be shifted by pressure buildup under the seals (Section II).

5. Available evidence suggests there were insufficient checks and balances for decisions involving both the schedule to complete well abandonment procedures and considerations for well safety (Section VI).

6. The decisions mentioned above were not identified or corrected by the operating management processes and procedures of BP or those of their contractors or by the oversight processes employed by the Minerals Management Service (MMS) or other regulators (Sections VI and VII).

7. Currently, there are conflicting views among experts familiar with the incident regarding the type and volume of cement used to prepare the well for abandonment. There are also conflicting views on the adequacy of the time provided for the cement to cure. These factors could have had a material impact on the integrity of the well (Section II).

8. The BOP did not control—or recapture control of—the well once it was realized that hydrocarbons were flowing into the well. Also, both the emergency disconnect system designed to separate the lower marine riser from the rest of the BOP and automatic sequencers controlling the shear ram and disconnect failed to operate (Section IV).

9. Given the large quantity of gas released onto the MODU and the limited wind conditions, ignition was most likely. However, the committee will be looking into reports (such as testimony provided at the MBI hearings) that various alarms and safety systems on the *Deepwater Horizon* MODU failed to operate as intended, potentially affecting the time available for personnel to evacuate (Section V).

10. The various failures mentioned in this report indicate the lack of a suitable approach for anticipating and managing the inherent risks, uncertainties, and dangers associated with deepwater drilling operations and a failure to learn from previous near misses (Section VI).

11. Of particular concern is an apparent lack of a systems approach that would integrate the multiplicity of factors potentially affecting the safety of the well, monitor the overall margins of safety, and assess the various decisions from perspectives of well integrity and safety. The "safety case" strategy required for drilling operations in the North Sea and elsewhere is one example of such a systems approach (Section VII).

II. CEMENTING OPERATIONS

Characteristics of the Well

A significant lost circulation event occurred in the Macondo well at 18,260 ft while drilling with a mud weight of 14.3 pounds per gallon (ppg).[5] This occurred in the open-hole section of the well, where multiple hydrocarbon reservoirs were encountered. Circulation was restored after lowering the mud weight to 14.17 ppg (and adding lost circulation material). The consensus interpretation of the lost circulation event is that the drilling mud pressure had exceeded the fracture pressure in one of the formations near 18,260 ft depth.[6]

As described below, a plan was devised to cement steel casing across the entire open-hole section of the Macondo well (extending from 17,168 ft to 18,304 ft) as a single operational step. One important geologic factor that made this plan quite difficult to carry out was the markedly different pore pressures of the permeable sand formations in the open-hole interval. These pore pressures, which decreased with depth, ranged from that equivalent to a mud weight of 14.1 ppg at 17,684 ft (a brine sand) to 12.6 ppg in the hydrocarbon-bearing sands encountered at 18,051 ft, 18,104 ft, and 18,202 ft.[7]

The decrease in pore pressure with depth in the open-hole section is associated with a corresponding decrease in the fracture gradient. This results in a very narrow range of safe operating pressures in the open-hole section during cementing. To stay in this range during cementing operations, the mud weight must be high enough to prevent inflow from the sands at relatively high pore pressure, but not so high that it could accidentally

[5] BP, *Deepwater Horizon* Accident Investigation Report, Sept. 8, 2010. See http://www.bp.com/sectiongenericarticle.do?categoryId=9034902&contentId=7064891. NOTE: The committee did not carry out a critical review of the BP report for this interim report and the committee comes to no conclusion about the overall findings and recommendations resulting from BP's investigation.

[6] The fracture pressure is the pressure at which a hydraulic fracture would propagate away from the well and cause a loss of drilling fluids. The fracture gradient is the fracture pressure per unit depth.

[7] BP, *Deepwater Horizon* Accident Investigation Report, Sept. 8, 2010.

hydraulically fracture the sands at lower pore pressure. In fact, lost circulation occurred during drilling at 18,260 ft with a mud weight of 14.3 ppg because the mud weight that was needed to prevent inflow from the brine sand at 17,684 ft (at a pore pressure of 14.1 ppg) was sufficient to exceed the fracture gradient in the deeper hydrocarbon-bearing sands with markedly low pore pressure. By slightly lowering the mud weight during drilling to 14.17 ppg, they attempted to complete drilling without hydraulically fracturing the hydrocarbon-bearing sands. As stated in the first few sentences about cement design in Section 2.1 of the BP *Deepwater Horizon* Accident Investigation Report, "The narrow pore pressure and fracture gradient conditions in the Macondo well … [were] a challenge for the BP and Halliburton personnel involved . . . the team needed a lightweight cement slurry that could be circulated in place without losing returns."[8] It appears, therefore, that accidental hydraulic fracturing of one or more of the hydrocarbon-bearing sands during cementing operations may have contributed to the failure of the cementing operations to achieve isolation of the hydrocarbon-bearing intervals.

Limitations of the Long String

During the drilling of the Macondo well, BP chose to install a long string of production casing instead of a liner tie back within the well casing to prepare the well for later production. The long string is a continuous length of casing that extends from the subsea wellhead to the bottom of the well. The alternative to running the long string is to use a liner that is tied back to the wellhead at a later date.[9] The liner is the same as the casing used at the bottom of the long string, except that the liner would be suspended by a mechanical hanger in the lower section of the previous casing string. In other words, the liner would only cover the open-hole portion of the well and extend upward only several hundred feet inside the previous casing string.

The use of a long string in lieu of a liner in a deep high-pressure well, particularly one with formations exhibiting markedly different pore pressures, raises multiple issues with regard to the time required for installation, the location of secondary flow barriers and use of the lockdown sleeve,[10] the capability to rotate the liner during cementing,[11] and the relative ease of well control (if all seals fail). These aspects and the implications of cementing across the entire open-hole section of the well will be considered by the committee.

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[8] BP, *Deepwater Horizon* Accident Investigation Report, Sept. 8, 2010.

[9] D. P. MacEachern, D.R. Algu, M. Cowan, K. Harris, and E. Snell, Advances in Tieback Cementing, SPE/IADC paper # 79907, SPE/IADC Drilling Conference, Amsterdam, Netherlands, Feb. 2003.

[10] A lockdown sleeve is a safety device installed on a casing hanger seal assembly to ensure the seals could not be shifted by pressure buildup under the seals.

[11] Pipe movement during cementing aids in displacing the mud in the annulus outside the casing with cement and helps the cement flow into smaller areas surrounding the casing.

Cementing Processes Employed

Nitrogen foamed cement was used to reduce the density of the cement and reduce the possibility of reservoir fracturing and lost returns.[12] The foamed cement was preceded by volumes of oil, mud spacer, and unfoamed base cement and was displaced by unfoamed base cement, mud spacer, and drilling mud. There are several factors that may have affected the ability of the cement to isolate the hydrocarbon-bearing formations adequately and seal the well.

The first factor has to do with cement type. The committee will investigate the characteristics of the cements used regarding the stability of the fluids during placement, the strengths attained by the cements when they set, the timing of setting and strength growth, and the potential changes in these properties if the cement were contaminated by other fluids. Questions have been raised about the strength of foam cement used in the well and whether sufficient time was allowed for the cement to set and gain strength before the negative-pressure test was conducted.

Second, a relatively small volume of cement was used to leave an exposed section of rock just below the previous casing string. This was done for the relief of pressure developed by well bore heating through short fractures in the rock in the section of hole not covered by cement. One consideration in using a smaller volume is the potential for contamination of the entire slurry volume simply because less cement is present. The committee will assess the potential degree to which contamination of the small volume of cement that was used might have compromised its effectiveness.

Third, to prepare the annular space around the casing for cementing, the well is usually cleaned by completely circulating the fluids from the bottom of the well to the surface. This is done to remove any formation cuttings from the inside of the casing (as it was run into the well) or from the annular volume around the casing before pumping in cement. A full circulation of fluids (bottoms-up circulation) according to standard industry practice was not done prior to cementing in the Macondo well.[13]

Fourth, when cement is pumped into a well, the flow rate should be high enough to place the mud spacer in turbulent flow. Turbulent flow, if it can be achieved, is regarded as an aid to mud removal in the annulus. It is not clear that the flow rates used during cementing (which were kept low to avoid excess pressure at the bottom of the casing) were sufficient to achieve turbulent flow.

Fifth, the casing should be centered in the well during cementing so that the cement fills the annular volume around the complete circumference of the well and thus reduces the likelihood for channeling. Six centralizers were placed on the casing with the goal of

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[12] J. White, S. Moore, M. Miller, and R. Faul, Foaming Cement as a Deterrent to Compaction Damage in Deepwater Production, IADC/SPE paper # 59136, IADC/SPE Drilling Conference, New Orleans, La., Feb. 2000.

[13] MBI hearing, July 22, 2010, testimony of John Guide, Wells Team Leader, BP.

centralizing it. Computer simulations of cementing operations by Halliburton indicated that there was significant potential for gas flow unless 21 centralizers were used.[14] While there is disagreement about the accuracy of these simulations, poorly centered casing would compromise the ability of the cement to completely seal the annulus surrounding the casing. This issue will be reexamined in light of the observed results and compared with generally accepted practices to understand the implications of the choice and placement of the centralizers.

Sixth, there were a number of unusual events during cementing operations. An extremely high pressure (almost 3,000 psi)[15] was required to prepare the float collar for cementing (instead of about 700 psi) potentially because of a presence of formation cuttings inside the casing.[16] Subsequently, pumping of the cement occurred at such unusually low pressure that there was concern that the casing might have been damaged.[17] Despite these unusual events, no cement bond log[18] was run (or other action taken) to verify that the cement behind the casing was capable of creating an effective barrier to hydrocarbon influx.

Finally, the hydrocarbon reservoirs encountered in the Macondo well are indicative of gas zones or zones with high ratios of gas to oil.[19, 20] In the event of a reduction of hydrostatic pressure in a well during the curing of cement, it is possible for gas to permeate the cement.[21] The committee will assess whether this process could have been a contributing factor to the failure of the cement to isolate the hydrocarbon-bearing formations.

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[14] Tommy Roth and John Gisclair, Halliburton, personal communication, September 26, 2010.

[15] BP, *Deepwater Horizon* Accident Investigation Report, Sept. 8, 2010.

[16] MBI hearing, July 22, 2010, testimony of John Guide, Wells Team Leader, BP.

[17] MBI hearing, August 24, 2010, testimony of Nathaniel Chaisson, Cementer, Halliburton.

[18] A cement bond log is a report of the cement thickness in a well bore obtained from using an imaging tool.

[19] National Oceanic and Atmospheric Administration (NOAA), Report of Flow Rate Technical Group, 2010.

[20] MBI hearing, August 24, 2010, testimony of Jesse Gagliano, Technical Sales Advisor, Halliburton.

[21] One way this reduction could occur is through a transient process as the cement changes from a fluid to a gel (semisolid) of lower strength compared with the final solid state. In the gel state, the cement does not fully transmit hydrostatic pressure to hold back gas in the reservoir as it did in the slurry state and as it will in its solidified state. If hydrostatic pressure is reduced, there is the potential for high-pressure gas to exchange with water released from the cement and form a channel in the cement. See the following sources: A. T. Bourgoyne, Jr., M. E. Chenevert, K. K. Millheim, and F. S. Young, Jr., *Applied Drilling Engineering*, SPE Textbook Series, Vol. 2, SPE, Richardson, Tex., 1991; D. C. Levine, E. W. Thomas, H. P. Bezner, and G. C. Tolle, Annular Gas Flow After Cementing: A Look at Practical Solutions, SPE Paper No. 8255-MS, SPE Annual Technical Conference, Las Vegas, Nev. Sept. 26, 1979; and S. M. Matthew and J. C. Copeland, Control of Annular Gas Flow in the Deep Anadarko Basin, SPE Paper No. 14980-MS, SPE Deep Drilling and Production Symposium, Amarillo, Tex., April 6–8, 1986.

While it is not possible to know with certainty if one or more of these factors contributed to the failure of the cement to seal the well, it is clear that there are several possible reasons why cementing of the Macondo well failed.

Shoe Track and Float Equipment

The bottom section of the casing in the Macondo well, called the "shoe track," was a section of casing about 189 ft long with a reamer-guide shoe at the bottom and a dual-flapper float collar on top.[22] This section of casing is meant to contain the last, or "tail," cement that is pumped—in this case unfoamed cement. The float collar flappers are designed to close after the cement is in place (and starts setting up) to prevent any flow back into the casing (and up the well) caused by hydrostatic pressure differences between the dense cement and drilling mud on the outside of the casing and the less dense displacement fluid on the inside. The float collar also acts as the landing point for the cementing plugs used during the job. The float collar used employed a differential fill tube that allowed mud to flow into the casing as it was run into the well. The fill tube in this case was designed to be pumped out of the float collar if the pump rate was higher than 5 barrels per minute. The top of the float collar in this well was at a depth of 18,115 ft measured from the rig floor. This placed the float collar above the base of the productive reservoir. The potential impacts of the location of the float collar will be evaluated by the committee, including whether it potentially precluded full evaluation of the cement job by logging. The committee will also consider available information related to the differential pressure to close the float collar flappers, the utility and the removal of the fill tube from the float collar, the utility of a float shoe rather than a guide shoe, and the possible fate of the cement placed in the shoe track.

III. INDICATIONS OF FLAWED CEMENT JOB AND START OF FLOW

Negative-Pressure Test

A negative-pressure test is used to indicate whether a cement barrier and other flow barriers have isolated formation fluids from the well bore. In concept, a negative-pressure test is quite simple: after cementing the annular space outside a section of steel casing, one purposely reduces the hydrostatic pressure inside the casing to test the integrity of the cement. If there is a good cement barrier in place, there should be no flow out of the well (or pressure buildup) after the pressure in the well is lowered.

When the negative-pressure tests in the Macondo well were carried out, the pressure inside the well was reduced by displacing around 1,000 ft of the drilling mud in the casing with less dense sea water. After the long string of casing was cemented in the Macondo well, repeated negative-pressure tests clearly showed a marked pressure buildup inside the casing after the drilling mud was displaced with sea water. In fact, Key

[22] H. Rogers and J. Heathman, Cementing Casing Equipment: Proper Selection Vital to Success, OTC paper 17083, Offshore Technology Conference, Houston, Tex. May, 2005.

Findings 1 and 3 in the BP *Deepwater Horizon* Accident Investigation Report[23] are, respectively, "The annulus cement barrier did not isolate the hydrocarbons" and "The negative-pressure test was accepted although well integrity had not been established." Proceeding to displace the dense drilling mud in the riser without an effective cement barrier was followed by the entry of hydrocarbons into the well and the eventual blowout and explosion.

Although there are no sanctioned guidelines or regulations governing how to run a negative-pressure test, the critical importance of such tests requires that every company have formal procedures established for carrying them out. Sometimes these procedures need to be adapted for the configurations of a particular drilling vessel and BOP. While there are also no formal guidelines for the interpretation and approval of the test results, it is clear that pressure buildup or flow out of a well is an irrefutable sign that the cement did not establish a flow barrier.

Well-Monitoring Services

There were several clear failures in the monitoring of the Macondo well that appear to have ultimately contributed to the blowout and explosion on the *Deepwater Horizon* MODU. Because detection of hydrocarbons, especially gas entering a well, is critical for maintaining safe operations, this report focuses on monitoring failures immediately prior to the first explosion on April 20, 2010. The possibility of hydrocarbons entering a well has such important implications for safety that it is common practice for the mud-logging company, drilling contractor, and operator to focus on determining whether this is occurring to ensure that remedial action can be taken immediately.

The time of the first explosion on the *Deepwater Horizon* MODU was 21:49. Available data cited in BP's Accident Investigation Report indicate that the well first became underbalanced at 20:52, with inflow being discernible at 20:58—that is, 51 minutes prior to the first explosion. By 21:08—at 41 minutes before the first explosion—it appears that 39 barrels of hydrocarbons were already in the well.[24]

A variety of factors may have led to hydrocarbons entering the Macondo well undetected for almost an hour before the first explosion. One of these factors was the running of a sheen test, which involved diverting the mud flow from the hydrocarbon detection instrumentation such that personnel may not have been able to detect increases in gas content in the drilling mud. Had the results of the negative-pressure test been correctly interpreted, the sheen test might not have been run at this time and would not have been a potential source of distraction from monitoring the well.

Another factor that may have led to hydrocarbons entering the well bore undetected was the simultaneous occurrence of activities with the mud system, including the transfer of drilling fluids from the mud tanks to a standby vessel (*Damon Bankston*). Usually, these

[23] BP, *Deepwater Horizon* Accident Investigation Report, Sept. 8, 2010.

[24] BP, *Deepwater Horizon* Accident Investigation Report, Sept. 8, 2010.

activities are carefully coordinated prior to operations. All personnel are made aware of their roles, safety issues, and the sequence that should occur, and responsible personnel oversee and coordinate all such activities. It appears that coordination of these procedures was lacking, which resulted in the failure to keep track of the material balance of the fluids in the well and riser. This process heavily relies on the monitoring of the pit levels and the fluids being pumped into the well and flowing out of the well. The decision to off-load drilling fluids at a critical time appears to have made it extremely difficult to determine the flow out of the well with accuracy. Had this off-loading activity been deferred, there is a possibility that the influx of reservoir fluids would have been detected.

Another well-monitoring activity that appears to have failed was the monitoring of the flow of the drilling fluid out of the well as the nitrogen foamed cement and spacers were being pumped into the well. Following the cement job, it was asserted that there were full returns during cementing, indicating that every barrel of injected cement was associated with a barrel of mud flowing out of the well.[25] Full returns would indicate that the cement was displacing mud from the casing annulus as planned. Full returns were cited as the reason BP did not run a cement bond log after cementing, which could have helped reveal that cementing operations had not gone as planned.[26] However, there appears to have been no monitoring system in place that could have confirmed that this was actually occurring during cementing operations.[27] In fact, data presented during the MBI hearings appear to indicate that during cementing operations, about 80 barrels more cement and spacers were pumped into the well than mud was flowing out of the well.[28] Such losses would be consistent with accidental hydraulic fracturing during cementing, as discussed above. While much of this difference may be the result of compression of the nitrogen in the cement,[29] losses during cementing still appear to have occurred. Moreover, nitrogen compression should have been anticipated, and a monitoring system should have been in place while cementing operations were going on to monitor returns and compensate for nitrogen compression as necessary. Had meaningful oversight of data on flow in and flow out been realized during cementing operations, problems with the cementing operations might have been recognized earlier and probably would have precipitated further diagnostic tests, such as running a cement bond log, before operations went ahead.

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[25] MBI hearing, July 22, 2010, testimony of John Guide, Wells Team Leader, BP; and August 24, 2010, testimony of Nathaniel Chaisson, Cementer, Halliburton.

[26] MBI hearing, July 22, 2010, testimony of John Guide, Wells Team Leader, BP.

[27] MBI hearing, August 24, 2010, testimony of Nathaniel Chaisson, Cementer, Halliburton.

[28] MBI hearing, August 25, 2010, Vincent Tabler, Cementer, Halliburton.

[29] During testimony to the committee on Sept. 26, 2010, BP presenters suggested that 50 barrels of the apparent loss was due to nitrogen compression from 60 barrels to 10 barrels.

IV. WELL CONTROL ACTIONS

Personnel on the *Deepwater Horizon* MODU attempted to take well control actions after substantial hydrocarbon flow had been initiated. None of the actions succeeded in controlling the well.

Flow Diversion

When hydrocarbon flow was finally noted, the *Deepwater Horizon* crew diverted the flow to the mud-gas separator. This resulted in gas exiting the vents located on the derrick, directly above the rig floor. It is unknown why personnel did not choose to divert the gas directly overboard.

Blowout Preventer

The BOP is relied on as a critical component for preventing uncontrolled hydrocarbon flows and avoiding a catastrophic blowout of a well. Various attempts were made to activate BOP functions on the *Deepwater Horizon* MODU, and there are indications that one of the annular preventers and perhaps a variable bore ram did operate to some degree, once actuated. These operations failed to control the flow, however. Furthermore, the blind shear ram (BSR), which was intended to shear the drill pipe and the production casing and seal the well bore in an emergency, was unable to recapture control, even after the explosion when hot stab procedures were initiated via remotely operated vehicle.

At this time, the exact nature of the mechanisms that constrained the utility of the BOP is unknown. The device has recently been recovered and is just starting to be subjected to detailed forensic analysis. Furthermore, the committee has been unable to access either the design and test data from the BOP manufacturer (Cameron) or the maintenance records from Transocean. Once theses data are made available, the committee will evaluate the multiple possible causal mechanisms that may have contributed to the failure to recapture control of the Macondo well.

Possible causal mechanisms that will be considered include failures resulting from design limitations, acceptance testing, operational setting, maintenance limitations, and/or damage from the initial explosion. These investigations will also explore the potential impact that material entrained in the hydrocarbon flow may have had on the operation of the BOP. Preliminary examinations of the lower riser sections and the BOP have identified multiple pieces of drill pipe. Furthermore, debris, possibly cement and/or formation rock, was entrained in the flow and landed on the *Damon Bankston*.

Much testimony has been proffered at the MBI hearings regarding the maintenance and inspection procedures, raising concerns regarding the adequacy of tests (such as the use of special test configurations versus operational configuration, low pressure tests of the BSR, etc.) and the approach used to perform preventative maintenance and recertification. The committee will assess the approaches used and make recommendations regarding future maintenance and inspection procedures.

The committee will pay particular attention to the design, test, and maintenance of the automatic mode function (designed to activate the BSR upon loss of hydraulic pressure and electric power from the rig) and of the emergency disconnect system that is intended to separate the lower marine riser from the rest of the BOP.

V. GAS DETECTORS, ALARMS, AND SAFETY SYSTEMS OF THE *DEEPWATER HORIZON* MODU

The *Deepwater Horizon* MODU, built in 2001, was a semisubmersible, dynamically positioned vessel designed for deepwater drilling. Once the uncontrolled flow of hydrocarbons had enveloped the deck of the rig on April 20, ignition was most likely, given the large volume of gas, the multitude of ignition sources on the rig, moderate temperature, and limited wind conditions. Testimony provided at the MBI hearings indicated, however, that various alarms and safety systems on the rig failed to operate as intended, potentially affecting the time available for personnel to evacuate.

Combustible gas detectors on the rig were designed to automatically activate visual and auditory alarms when monitored gas concentrations exceeded a predetermined level of safety. Some of those detectors were designed to activate systems that automatically closed dampers and shut down fans to prevent ambient gas flow into specific zones on the rig. Similar kinds of emergency closures and shutdowns on other parts of the rig required manual activation in response to a combustible gas detector alarm. According to MBI testimony, inspectors working on behalf of the U.S. Coast Guard and MMS verified that components of the rig's safety systems were in place and functioning properly.[30] Rig personnel testified, however, that several fire and gas detectors were not functioning or had been inhibited because of frequent false alarms.[31] In an inhibited mode, automatic systems would display an alert on one or more control panels upon detection of high levels of gas; subsequent responses would require manual activation. Testimony also indicated that although systems were in place to determine the operating status of individual gas detectors and alarms, there was no procedure for tracking the status of all alarms on the rig.[32]

Engines on the rig were equipped with devices designed to shut them down automatically when predetermined overspeed conditions occurred. It was reported that the air intake controls for the engine room on the rig were not set up to automatically close upon detection of high concentrations of gas. According to testimony, at least one engine on the vessel appeared to speed up excessively prior to the first explosion.[33] At this time, the

[30] MBI hearing, May 11, 2010, testimony of Robert Neal, Inspector, MMS; and Eric Neal, Inspector, MMS; and May 12, 2010, testimony of Capt. Vern Gifford, 8th District Chief of Prevention, U.S. Coast Guard.

[31] MBI hearing, July 23, 2010, testimony of Michael Williams, Chief Engineer Technician, Transocean.

[32] MBI hearing, July 23, 2010, testimony of Michael Williams, Chief Engineer Technician, Transocean.

[33] MBI hearing, May 26, 2010, testimony of Douglas Brown, Chief Mechanic, Transocean; and July 23, 2010, testimony of Michael Williams, Chief Engineer Technician, Transocean.

extent to which an engine in overspeed condition contributed to gas ignition on the rig is unknown.

During the course of its study, the committee will examine evidence on the maintenance, testing, operating procedures, and reliability of alarms and other safety systems on the *Deepwater Horizon* MODU. It will also assess the adequacy of such systems given the hazards present on such vessels and the need to provide adequate time for emergency response by rig personnel.

VI. MANAGEMENT OF OPERATIONS

The engineering and drilling operations associated with drilling offshore, especially in deep water, are exceedingly complex, in that they involve a wide range of technologies and a large number of contractors. Managing the overall effort to achieve safe and efficient operations is a challenging task. These challenges are compounded by the physical separation of the effort from the management and engineering staff and the employment of multiple service contractors providing expertise in many critical areas. The committee has been analyzing testimony provided at the MBI hearings to assess the efficacy of the management systems in place at the time of the disaster and will be evaluating other systems employed elsewhere (both in the United States and overseas) in this and other industries where high risks are present and safety must be managed actively.

Delegation of Decision-Making Authorities

Witnesses at the MBI hearings exhibited a variety of perspectives with regard to the assignment of responsibility aboard the *Deepwater Horizon* MODU. Testimony suggested that decision making was a "team process" involving personnel from various companies, or that the offshore installation manager (OIM) and/or the well site leader ("company man") were responsible for individual decisions.[34] Also, concern was expressed by rig personnel regarding the change in well site leader just prior to critical temporary abandonment procedures.[35] A lack of specific identification of authority appears in testimony regarding the involvement of shore-based personnel. The decision to accept the results of the negative-pressure test as satisfactory—rationalized as being the result of some hypothesized "bladder effect" (or annular compression)[36]—without review by adequately trained shore-based engineering or management personnel[37] suggests a lack of onboard expertise and of clearly defined responsibilities and the associated limitations of authority. Similarly, the decision to disregard the OptiCem™ modeling

[34] MBI hearing, May 26, 2010, testimony of Capt. Carl Smith, Master and OIM of the *Ocean Courage*, Diamond Offshore; May 26, 2010, testimony of Douglas Brown, Chief Mechanic, Transocean; and May 28, 2010, testimony of Miles Ezell, Senior Tool Pusher, Transocean.

[35] MBI hearing, August 23, 2010, testimony of Paul Johnson, Rig Manager, Transocean.

[36] BP, *Deepwater Horizon* Accident Investigation Report, Sept. 8, 2010.

[37] MBI hearing, July 22, 2010, testimony of John Guide, Wells Team Leader, BP.

results concerning the number of centralizers to be run on the casing without consulting in-house experts suggests a lack of management discipline that is inconsistent with the stakes involved. The committee will be examining weaknesses in the management structure, the delegation of authorities, and the implications of the structure of the industry and the personnel employed by it.

Standards for Education, Training, and Professional Certification

As described in testimony of witnesses at the MBI hearings, standards for education, training, and professional certification of private-sector decision-making personnel involved in drilling operations are relatively minimal compared with other safety-critical industries. Personnel on the *Deepwater Horizon* MODU were mostly trained on the job, and this training was supplemented with limited short courses (such as 1 week of well control school every few years). While this appears to be consistent with industry standard practice and current regulations (such as 46 CFR 10.470 for OIMs), it is not consistent with other safety-critical industries such as nuclear power or chemical manufacturing. The committee plans to further assess the appropriate qualifications of key personnel both on deepwater drilling rigs and ashore, as needed, to provide for safe operations and protect the public interest.

Use of Real-Time Data by Management

Much of the drilling, “mud-logging,” and operational rig data obtained during casing and cementing processes were sent onshore in near real time; however, no onshore monitoring process was employed to assess what was happening in the well (and on board the *Deepwater Horizon* MODU) on a continuing basis, as is done by other operating companies. The committee will consider the potential value of such real-time operations centers as a means of providing oversight and support.

Confluence of Cost, Schedule, and Safety Responsibilities

Testimony at the MBI hearing indicated that the BP wells team leader was responsible for cost and schedule in addition to decisions affecting the integrity and safety of the well. Also, the testimony failed to discern any standard practice employed to guide the tradeoffs between cost and schedule and the safety implications of the many decisions (that is, a risk management approach). The often-made assertion at the MBI hearing that safety was never compromised[38] suggests that the risks that are an inherent part of engineering processes in this and many other industries were not fully recognized. As it appears from the testimony that many of the pivotal choices made for the drilling operation and temporary abandonment of the well were likely to result in less cost and less time relative to other options, the committee will be examining the use of a separate path of reporting and oversight employed elsewhere to ensure that decisions made in the interest of cost and schedule do not unreasonably compromise safety. Furthermore, as one alternative, the committee will consider the utility of an independent technical authority similar to that employed within the submarine and nuclear communities. Such

[38] For example, MBI hearing, July 22, 2010, testimony of John Guide, Wells Team Leader, BP.

authorities have been shown to provide checks and balances to operations by enforcing standards and reviewing any deviations.

Learning from Experiences

The loss of circulation in the Macondo well on March 8, 2010, while drilling at 18,260 ft represented an opportunity to recognize the challenges of the well and to take measures for mitigating future risks. This apparently was not done effectively, as evidenced by the decision to proceed with temporary abandonment procedures despite negative-pressure test indications of potential problems. The experience of the committee members suggests that in an effective risk management approach reflecting a safety culture, “near misses” provide opportunities to improve, and the reporting of errors, omissions, and questionable results is highly encouraged. Furthermore, the committee will be exploring ways to establish practices and standards and foster continuous improvement in safety culture within the industry.

VII. OVERSIGHT AND REGULATION

Qualifications of Oversight Personnel

As indicated in the previous section, effective overall management of deepwater exploration is a challenging task. Likewise, effective regulation and oversight of this highly complex enterprise also presents a substantial challenge. After its initial information gathering, however, the committee has not seen a clear indication that there are adequate standards for education, training, and professional certification of personnel involved in the oversight and regulation of deepwater exploration operations. For example, the U.S. Department of the Interior’s Outer Continental Shelf Safety Oversight Board found that MMS did not have a formal training and certification program for its inspectors. The oversight board also found that there is little opportunity for higher education and career advancement for inspectors.[39, 40] The committee will consider approaches to ensure individuals involved in regulatory oversight have qualifications that are appropriate for meeting the challenges of this endeavor.

Multiplicity of Regulatory Agencies and Classification Societies

MMS was responsible for review and approval of permits and plans (and their modifications) for the drilling and completion of the Macondo well. MMS personnel also conducted inspections on board the *Deepwater Horizon* MODU. As the flag state for the *Deepwater Horizon* MODU, the Republic of the Marshall Islands had oversight

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[39] U.S. Department of the Interior Outer Continental Shelf Safety Oversight Board, Report to Secretary of the Interior Ken Salazar, Sept. 1, 2010. http://www.doi.gov/news/pressreleases/loader.cfm?csModule=security/getfile&PageID=43677.

[40] On May 19, 2010, Secretarial Order No. 3299 separated the responsibilities currently performed by MMS and reassigned those responsibilities to the newly established Office of Natural Resources Revenue (ONRR), BOEM, and the Bureau of Safety and Environmental Enforcement (BSEE).

responsibilities that included conducting safety inspections and surveys and monitoring compliance with national and international safety standards. The American Bureau of Shipping and Det Norske Veritas (two classification societies) conducted surveys, audits, and other activities required for issuance of certificates on behalf of the Marshall Islands. The U.S. Coast Guard had responsibility for ensuring the *Deepwater Horizon* MODU met the safety requirements for rigs operating in the U.S. Outer Continental Shelf Region.

From testimony, it appears that the various organizations mentioned above sometimes were not certain of the oversight duties actually being carried out by other organizations.[41] For example, MMS regulators assumed that the entire *Deepwater Horizon* MODU, including drilling equipment, had been classed, when that was not the case.[42, 43] Also, it was not apparent whether any of the organizations had developed an overall perspective for oversight of the exploratory operation. In addition, the committee notes the apparent lack of requirements or standard industry practice for a systems approach in assessing the full range of factors affecting the safety of drilling operations in the U.S. Outer Continental Shelf Region. The safety case[44] strategies required by the United Kingdom Health and Safety Executive,[45] the National Offshore Petroleum Safety Authority in Australia,[46] and other authorities illustrate the application of a systems approach.

The committee will assess the extent to which there are gaps, redundancies, and substantial uncertainties concerning the responsibilities of multiple regulatory agencies and classification societies overseeing deepwater drilling operations. The committee notes that in considering the effectiveness of various regulatory structures, it is not within its purview to assess the extent to which specific organizations have complied with relevant laws and regulations.

Standards Development

In setting standards, MMS tended to rely substantially on technical standards developed by subject matter experts in industry.[47] In particular, the American Petroleum Institute (API) develops equipment and operating standards, codes, and recommended practices for the offshore oil and gas industry. In many cases, API-recommended practices are

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[41] MBI hearing, May 12, 2010, testimony of Capt. Thomas Heinan, Deputy Commissioner Maritime Affairs, Republic of the Marshall Islands; and May 26, 2010, testimony of John Forsyth, Assistant Chief Surveyor, American Bureau of Shipping.

[42] David Dykes, Chief, Office of Safety Management, BOEM, personal communication, August 12, 2010.

[43] Class means certifying that a vessel meets a classification society's rules for design, construction, and maintenance.

[44] A safety case is a body of evidence for determining whether a system is adequately safe for a given application in a given operating environment.

[45] See www.hse.gov.uk/offshore/scham/index.htm.

[46] See www.nopsa.gov.au/safety.asp.

[47] Michael Bromwich, Director, BOEM, personal communication, August 12, 2010.

standardized and then incorporated or referenced by government regulations. In its recent regulations, MMS had referenced about 80 of the approximately 240 standards developed by API that are related to exploration and development.[48] It is not apparent to the committee that MMS had sufficient in-house expertise and technical capabilities to independently evaluate the adequacy of the technological standards and practices that industry developed for deepwater drilling.

Furthermore, MMS standards and regulations are often developed through a multiyear consensus process in response to past events or trends. MMS had been working for at least 9 years on a draft regulation concerning secondary control systems for BOP stacks used in deepwater drilling operations.[49] Reliance on a retrospective approach to standards development necessarily lags behind the rapid development of new technologies for deepwater drilling. The committee will be looking with interest at new standards and regulations being developed for deepwater exploration and will assess their potential for promoting the use of the safest available technologies and practices.

Independent Review of Critical Safety Equipment and Well Completion Steps

Some components that are critical to the safety of oil drilling operations are not required to be independently certified by a third party (such as a classification society) or by the relevant regulatory agency. MMS did not directly oversee the initial and subsequent certifications of BOPs. Instead, the operator was to self-certify the BOP.[50] Also, MMS was not directly involved in overseeing critical steps in the well completion process. For example, little guidance was provided for conducting and interpreting negative-pressure tests of well integrity. The committee will consider approaches for ensuring that independent review is provided for critical equipment and practices associated with deepwater exploration.

VIII. COMPLETING THE COMMITTEE'S STUDY

In carrying out the remainder of its study, the committee will continue to gather information (via site visits, invited presentations, and requests for documents and data) to address issues discussed in this report as well as other issues relevant to its scope of work. The committee will track the forensic analysis of the recovered BOP and other analyses being carried out for MBI. The committee will examine the new regulations and other initiatives (of governmental and private organizations) being developed for deepwater exploration in the U.S. Outer Continental Shelf Region. In addition, the

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[48] U.S. Department of the Interior Outer Continental Shelf Safety Oversight Board Report to Secretary of the Interior Ken Salazar. September 1, 2010. http://www.doi.gov/news/pressreleases/loader.cfm?csModule=security/getfile&PageID=43677.

[49] MBI hearing, May 12, 2010, testimony of Michael Saucier, Regional Supervisor for Field Operations in the Gulf of Mexico Region, MMS.

[50] MBI hearing, May 12, 2010, testimony of Michael Saucier, Regional Supervisor for Field Operations in the Gulf of Mexico Region, MMS.

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committee will examine approaches for regulation and oversight of deepwater exploration in the North Sea and other foreign locations. All of these activities are intended to inform the committee's deliberations for its final report, due by June 2011. That report will provide the committee's overall findings regarding the causes of the *Deepwater Horizon* incident and recommend approaches for minimizing the likelihood of similar events occurring in the future.

Sincerely,

Donald C. Winter

Chair, Committee for the Analysis of Causes of the *Deepwater Horizon* Explosion, Fire, and Oil Spill to Identify Measures to Prevent Similar Accidents in the Future

Appendix A

Biographical Information on the Committee for the Analysis of Causes of the *Deepwater Horizon* Explosion, Fire, and Oil Spill to Identify Measures to Prevent Similar Accidents in the Future

Donald C. Winter *(Chair)* is professor of engineering practice in the Department of Naval Architecture and Marine Engineering at the University of Michigan. He served as the 74th Secretary of the Navy from January 2006 to March 2009. As Secretary of the Navy, he led America's Navy and Marine Corps Team and was responsible for an annual budget in excess of $125 billion and almost 900,000 people. Previously, Dr. Winter served as a corporate vice president and president of Northrop Grumman's Mission Systems sector. In that position, he oversaw operation of the business and its 18,000 employees, providing information technology systems and services; systems engineering and analysis; systems development and integration; scientific, engineering, and technical services; and enterprise management services. Dr. Winter also served on the company's corporate policy council. Previously, he served as president and chief executive officer of TRW Systems; vice president and deputy general manager for group development of TRW's Space and Electronics business; and vice president and general manager of the defense systems division of TRW. From 1980 to 1982, he was with the Defense Advanced Research Projects Agency as program manager for space acquisition, tracking, and pointing programs. Dr. Winter received a doctorate in physics from the University of Michigan. He is also a graduate of the University of Southern California Management Policy Institute; the University of California, Los Angeles, Executive Program; and the Harvard University Program for Senior Executives in National and International Security. In 2002, he was elected a member of the National Academy of Engineering.

Paul M. Bommer is a senior lecturer in petroleum engineering in the Department of Petroleum and Geosystems Engineering at the University of Texas at Austin. He is also a major contributor to publications of the University of Texas Petroleum Extension Service (PETEX), including books on oil well drilling and fundamentals of petroleum. Recently, Dr. Bommer was a member of the National Oceanic and Atmospheric Administration–U.S. Geological Survey Flow Rate Technical Group concerning estimates of the rate at which oil was escaping from the BP Mississippi Canyon 252-001 (Macondo) well. In 1979, he co-founded Bommer Engineering Co., which is an oil and gas consulting company specializing in drilling and production operations and oil and gas appraisals. He is a registered professional engineer in the State of Texas. He received a doctorate in petroleum engineering from the University of Texas at Austin.

Chryssostomos Chryssostomidis is the Doherty Professor of Ocean Science and Engineering at the Massachusetts Institute of Technology (MIT). He was appointed to the faculty of MIT in 1970. In 1982, he was made a full professor and was also appointed director of the MIT Sea Grant College Program. In 1989, he established the MIT Sea Grant Autonomous Underwater Vehicles (AUV) Laboratory to develop technology and systems for advanced autonomous surface and underwater vehicles. His more than 100 publications display his wide range of interests, including design methodology for ships, vortex-induced response of flexible cylinders, underwater vehicle design, and design issues in advanced shipbuilding, including the all-electric ship and T-Craft. Professor Chryssostomidis is a licensed engineer in the state of Massachusetts and has served on several National Research Council committees focusing on shipbuilding and marine issues. He received a doctorate in ship systems analysis from MIT.

David E. Daniel is president of The University of Texas at Dallas. Previously, he was dean of engineering at the University of Illinois. Earlier, Dr. Daniel was L. B. Meaders Professor of Engineering at the University of Texas at Austin, where he taught for 15 years. Dr. Daniel has conducted research in the area of geoenvironmental engineering, including research on drilling fluids, containment and management of those fluids, and fluid pressure control in the subsurface. He served as chair of the American Society of Civil Engineers' External Review Panel, which evaluated the failure of the New Orleans levees. He also served as a member of the National Research Council's Nuclear and Radiation Studies Board, the Board on Energy and Environmental Systems, and the Geotechnical Board. Dr. Daniel received a doctorate in civil engineering from the University of Texas at Austin. He was elected to the National Academy of Engineering in 2000.

Thomas J. Eccles is a rear admiral in the U.S. Navy. He currently serves as chief engineer and deputy commander for Naval Systems Engineering, Naval Sea Systems Command. Previously, RDML Eccles served at sea aboard USS *Richard B. Russell* (SSN 687) and USS *Gurnard* (SSN 662). As an engineering duty officer, he served at Mare Island Naval Shipyard and as project officer for USS *Parche* (SSN 683) and assistant program manager for deep ocean engineering in the Navy's Deep Submergence Systems Program. He served twice in the Virginia Class Submarine Program, directing design and construction. He was executive assistant to the commander, Naval Sea Systems Command. RDML Eccles was Seawolf program manager through the delivery of USS *Jimmy Carter* (SSN 23), where his team was awarded the Meritorious Unit Commendation, then program manager for Advanced Undersea Systems, responsible for research and development submarines, submarine escape and rescue systems, and atmospheric diving systems. He was also program manager for the design and construction of the unmanned autonomous submarine *Cutthroat* (Large-Scale Vehicle 2). RDML Eccles' previous flag officer assignments included deputy commander for Undersea Warfare and Undersea Technology in the Naval Sea Systems Command (NAVSEA) and commander of the Naval Undersea Warfare Center. In addition to receiving a master of science degree in mechanical engineering from the Massachusetts Institute of Technology (MIT), he received the Naval Engineer degree and a master's degree in management from MIT's Sloan School of Management.

Edmund P. Giambastiani, Jr., is a retired U.S. Navy admiral who served as the seventh vice chairman of the Joint Chiefs of Staff (the nation's second highest ranking military officer) from 2005 until he retired in 2007. While vice chairman, he also served as the co-chair of the Defense Acquisition Board; chair of the Joint Requirements Oversight Council; and member of the National Security Council Deputies Committee, the Nuclear

Weapons Council, and the Missile Defense Executive Board. He previously served as commander, U.S. Joint Forces Command; as NATO's supreme allied commander, transformation; and as senior military assistant to the U.S. Secretary of Defense. ADM Giambastiani was a career nuclear submarine officer who gained extensive operational experience, including command at the submarine, squadron, and fleet levels. His operational assignments included several in which he was responsible for demanding at-sea operations and for the development of new technologies and experimental processes. He commanded Submarine NR-1, the Navy's only nuclear-powered deep-diving ocean engineering and research submarine, USS *Richard B. Russell* (SSN-687), and the Submarine Force U.S. Atlantic Fleet. He currently serves on the boards of the Boeing Company, Monster Worldwide, and QinetiQ Group PLC and does independent consulting. In addition, since retirement, he has served on a number of U.S. government advisory boards, investigations, and task forces. He currently serves as chairman of the Secretary of the Navy's Advisory Panel. ADM Giambastiani graduated from the U.S. Naval Academy with leadership distinction.

David A. Hofmann is Professor of Organizational Behavior at the University of North Carolina's Kenan-Flagler Business School. Dr. Hofmann conducts research on leadership, organizational and work group safety climates, and organizational factors that affect the safety behavior and performance of individual employees. His research has contributed significantly to the scientific foundation of assessment tools used to evaluate the safety and organizational climates of organizations—such as the National Aeronautics and Space Administration after the Columbia accident—and to help plan interventions to improve safety climate. Dr. Hofmann's research has appeared in *Academy of Management Journal*, *Academy of Management Review*, *Journal of Applied Psychology*, *Journal of Management*, *Organizational Behavior and Human Decision Processes*, and *Personnel Psychology*. He also has published or has forthcoming numerous book chapters on leadership, safety issues, and multilevel research methods. In 2003, he edited a scholarly book on safety in organizations (*Health and Safety in Organizations: A Multilevel Perspective*), and he has a second edited book forthcoming on *Errors in Organizations*. Dr. Hofmann has received the American Psychological Association's Decade of Behavior Award, the Society of Human Resource Management's Yoder-Heneman Award, and has been a Fulbright Senior Scholar. Prior to arriving at the University of North Carolina at Chapel Hill, he was a faculty member at Purdue University, Texas A&M University, and Michigan State University. Dr. Hofmann consults, conducts applied research, and leads executive workshops for a variety of governmental organizations and private corporations. He received a doctorate in industrial and organizational psychology from Pennsylvania State University.

Roger L. McCarthy is a private engineering consultant and a director of Shui on Land, Ltd., which is involved in large-scale urban redevelopment in the People's Republic of China. Dr. McCarthy has substantial experience in the analysis of failures of an engineering or scientific nature. He has investigated the grounding of the Exxon *Valdez*, the explosion and loss of the *Piper Alpha* oil platform in the North Sea, the fire and explosion on the semisubmersible *Glomar Arctic II*, and the rudder failure on the VLCC Amoco *Cadiz*. Previously, Dr. McCarthy was chairman emeritus of Exponent, Inc., and chairman of Exponent Science and Technology Consulting Co., Ltd. (Hangzhou, China). In 1992, he was appointed by the first President Bush to the President's Commission on the National Medal of Science. Dr. McCarthy received a doctorate in mechanical engineering from the Massachusetts Institute of Technology. He was elected to the National Academy of Engineering in 2004.

Najmedin Meshkati is a professor of engineering at the University of Southern California. He is also a Jefferson Science Fellow, in which capacity he is serving as a senior science and engineering advisor to the Office of the Science and Technology Adviser to the Secretary of State. For the past 25 years, Dr. Meshkati has been teaching and conducting research on risk reduction and reliability enhancement of complex technological systems, including nuclear power, aviation, and the petrochemical and transportation industries. He has written many articles on human factors, safety culture, and accident causation. In addition, Dr. Meshkati has inspected many petrochemical and nuclear power plants around the world, including Chernobyl in 1997. He worked with the U.S. Chemical Safety and Hazard Investigation Board as an expert advisor in human factors and safety culture on the investigation of the BP refinery explosion in Texas City. He was elected Fellow of the Human Factors and Ergonomics Society in 1997. Dr. Meshkati served as a member of the National Research Council (NRC) Committee on Human Performance, Organizational Systems, and Maritime Safety. He also served as a member of the NRC Marine Board's Subcommittee on Coordinated Research and Development Strategies for Human Performance to Improve Marine Operations and Safety. Dr. Meshkati received a doctorate in industrial and systems engineering from the University of Southern California.

Keith K. Millheim is director and owner of Strategic Worldwide, LLC, which provides advisory services to oil companies for oil and gas exploration and production. He is also managing director of Nautilus International, LLC, which conducts research and development projects pertaining to deepwater well intervention and early deepwater reservoir appraisal. In 2007, he retired from Anadarko Petroleum Corporation as a distinguished advisor. He was also director of the Mewbourne School of Petroleum and Geological Engineering at the University of Oklahoma in Norman; director of the Institute of Drilling, Production and Economics at the Mining University of Leoben in Austria; a research consultant and drilling manager for Amoco Production Company; and a petroleum engineer for Conoco. Dr. Millheim's research interests focus on the implementation of new technology in petroleum drilling. He has experience in deepwater drilling in the Gulf of Mexico, Brazil, the North Sea, and West Africa. He is currently serving as a member of the National Research Council Committee on the Review of the Scientific Accomplishments and Assessment of the Potential for Future Transformative Discoveries with U.S.-Supported Scientific Ocean Drilling. Dr. Millheim received a doctorate in mining engineering from the University of Leoben. He was elected to the National Academy of Engineering in 1990.

Elisabeth Pate-Cornell is the Burt and Deedee McMurtry Professor and chair of the Department of Management Science and Engineering at Stanford University. Her specialty is engineering risk analysis with application to complex systems (space, medicine). Her research has focused on explicit consideration of human and organizational factors in the analysis of failure risks and, recently, on the use of game theory in risk analysis. Applications in the past few years have included counterterrorism and nuclear counterproliferation problems. Dr. Pate-Cornell is a member of several boards, including Aerospace, Draper, and In-Q-Tel. She was a member of the President's Foreign Intelligence Advisory Board until December 2008. Dr. Pate-Cornell received a doctorate in engineering economic systems from Stanford University. She was elected to the National Academy of Engineering in 1995.

Robert F. Sawyer is the Class of 1935 Professor of Energy, emeritus, with the Department of Mechanical Engineering at the University of California, Berkeley. His research interests are in combustion, pollutant formation and control, regulatory policy, rocket propulsion, and fire safety. Dr. Sawyer served as chairman of the California Air Resources Board; chairman of the energy and resources group of the University of California, Berkeley; chief of the liquid systems analysis section at the U.S. Air Force Rocket Propulsion Laboratory; and president of the Combustion Institute. He has served on numerous National Research Council (NRC) committees and is a member of the NRC's Board on Environmental Studies and Toxicology. Dr. Sawyer holds a doctorate in aerospace science from Princeton University. He was elected to the National Academy of Engineering in 2008.

Jocelyn E. Scott is chief engineer and vice president of DuPont Engineering, Facilities and Real Estate. She joined DuPont in 1984 in the DuPont Photosystems and Electronic Products division in Rochester, NewYork. Ms. Scott served in numerous engineering and operations activities and carried out research and development assignments in various DuPont businesses. She was manager for various engineering positions and was named executive assistant to the chairman and CEO. In 2002, she was named director of DuPont Engineering and Research Technology, and in 2004 she became director of Capital Asset Productivity. In 2006, she was named director of DuPont Leveraged Operations; later that year, she became managing director, Facilities and Capital Asset Productivity. She was named vice president of DuPont Engineering in January 2008 and appointed to her current position in September 2008. Ms. Scott chaired the 2008 national conference of the Construction Users Roundtable. In addition to participating on various industry advisory boards, she has served on the Committee of Visitors for the Division of Chemical, Bioengineering, Environmental, and Transport Systems of the National Science Foundation. She received a master's degree in chemical engineering practice from the Massachusetts Institute of Technology.

Arnold Stancell is Turner Professor of Chemical Engineering, emeritus, at the Georgia Institute of Technology, and earlier in his career he was offered tenure at the Massachusetts Institute of Technology (MIT) but decided on a career in industry. He had a 31-year career with Mobil Oil, where he was vice-president, U.S. Exploration and Production, offshore and onshore, and subsequently vice-president, International Exploration and Production for Europe, including the United Kingdom, Norway, the Netherlands, and Germany, and the Middle East, including Saudi Arabia, Qatar, Abu Dhabi. He led the development of the now $70 billion natural gas production and liquefied natural gas joint venture between Mobil and Qatar. Previously, he held senior executive positions in Chemicals and Marketing and Refining. He started at Mobil in 1962 in research and development and has nine U.S. patents in petrochemical processes. Dr. Stancell received an Sc.D. in chemical engineering from MIT, and his thesis was on reservoir rock wettability and oil recovery. He is a licensed professional engineer in New York and Connecticut. He was elected to the National Academy of Engineering in 1997.

Mark D. Zoback is the Benjamin M. Page Professor of Geophysics at Stanford University. He is also codirector of the Stanford Rock Physics and Borehole Geophysics industrial consortium. Dr. Zoback conducts research on in situ stress, fault mechanics, and reservoir geomechanics. He is the author of a textbook entitled *Reservoir Geomechanics* and was co–principal investigator of the San Andreas Fault Observatory at Depth (SAFOD), the scientific drilling project that drilled and sampled the San Andreas Fault at 3 km depth. He also serves as a senior adviser to Baker Hughes, Inc. Prior to joining Stanford in 1984, Dr. Zoback worked at the U.S. Geological Survey, where he served as chief of the Tectonophysics Branch. He is the 2008 recipient of the Walter H. Bucher medal from the American Geophysical Union. He received a doctorate in geophysics from Stanford University.

Appendix B

Statement of Task

At the request of the U.S. Department of the Interior, a National Academy of Engineering/National Research Council (NAE/NRC) committee will be convened to examine the probable causes of the *Deepwater Horizon* explosion, fire, and oil spill in order to identify measures for preventing similar harm in the future. The NAE/NRC committee's review will focus on an assessment of technologies and practices and include the following tasks:

1. Examine the performance of the technologies and practices involved in the probable causes of the explosion, including the performance of the blowout preventer and related technology features, which ultimately led to an uncontrolled release of oil and gas into the Gulf of Mexico.
2. Identify and recommend available technology, industry best practices, best available standards, and other measures in the United States and around the world related to oil and gas deepwater exploratory drilling and well completion to avoid future occurrence of such events.

The NAE/NRC committee will issue two reports:

1. An interim letter report that addresses the probable causes of the *Deepwater Horizon* explosion, fire, and oil spill and identifies potential measures to avoid such events. This report will be issued no later than October 31, 2010, with the intent that the committee's preliminary findings and/or recommendations will be considered in the joint investigation by the Minerals Management Service (Bureau of Ocean Energy Management, Regulation, and Enforcement) and the U.S. Coast Guard, the Presidential Commission, and any other formal review or investigation of the *Deepwater Horizon* explosion, fire, and oil spill.
2. A final report that presents the committee's final analysis, including findings and/or recommendations, called for in Tasks 1 and 2 above by June 1, 2011 (prepublication version of report), with relevant dissemination activities and a final published version to follow by December 30, 2011.

If at any time in the course of the NAE/NRC committee information-gathering activities, information is acquired indicating a public health or safety risk, the NRC will notify the Department of the Interior of the availability of such information.

The project is sponsored by the U.S. Department of the Interior.

Appendix C

Information-Gathering Activities of the Committee

In the course of preparing this report, the committee met eight times. At three of those meetings, oral presentations were made by the following individuals in public session at the invitation of the committee: David Hayes, U.S. Department of the Interior; Michael Bromwich and David Dykes, Bureau of Ocean Energy Management, Regulation, and Enforcement; Erik Milito, Roland Goodman, David Soffrin, and Andy Radford, American Petroleum Institute; Eric Christensen, U.S. Coast Guard; Brian Poskaitis, The Republic of the Marshall Islands, Office of the Maritime Administrator; Kenneth Richardson, American Bureau of Shipping; Steve Vorenkamp, Wild Well Control, Inc.; Mark Bly, Fereidoun Abbassian, Tony Brock, Kent Corser, Steve Robinson, and Dave Wall, BP; Thomas Roth and John Gisclair, Halliburton; and C. R. (Charlie) Williams II, Shell. Some of the presenters were joined by additional representatives of their respective organizations. Interested members of the public at large were also given an opportunity to speak to the committee. In accordance with institutional procedures, the committee visited facilities of BP, Hydril, Shell, and the U.S. Coast Guard that were not open to the public. Committee members also attended the July and August hearings of the Marine Board of Inquiry.

The committee made use of a variety of documents and other sources of information, including some that have been designated as proprietary by the submitters.

Appendix D

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise in accordance with procedures approved by the National Research Council Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report: Benton F. Baugh, Radoil, Inc.; Vice Admiral James C. Card, U.S. Coast Guard (Retired); John S. Carroll, Massachusetts Institute of Technology; B. John Garrick, Laguna Beach, CA; Richard S. Hartley, B&W Pantex; Trevor O. Jones, ElectroSonics Medical Inc.; Thomas Kitsos, Bethesda, MD; Larry W. Lake, University of Texas at Austin; Nancy G. Leveson, Massachusetts Institute of Technology; Rear Admiral Malcolm MacKinnon, III, (U.S. Navy, Retired), MacKinnon-Searle Consortium, LLC; J. R. Anthony Pearson, Imperial College, Cambridge, United Kingdom (Emeritus Professor) and Consultant, Schlumberger Cambridge Research Ltd; Frank J. Schuh, Drilling Technology, Inc.; and Richard J. Stegemeier, Unocal Corporation (Chairman Emeritus).

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Robert A. Frosch, Harvard University, and C. Michael Walton, University of Texas at Austin. Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.