Deepwater Horizon Investigation
Investigation Context

- Terms of Reference
- Investigation Team
- Data and Analysis
- Investigation Limitations
Eight Barriers Were Breached

Well integrity was not established or failed
1. Annulus cement barrier did not isolate hydrocarbons
2. Shoe track barriers did not isolate hydrocarbons

Hydrocarbons entered the well undetected and well control was lost
3. Negative pressure test was accepted although well integrity had not been established
4. Influx was not recognized until hydrocarbons were in riser
5. Well control response actions failed to regain control of well

Hydrocarbons ignited on the *Deepwater Horizon*
6. Diversion to mud gas separator resulted in gas venting onto rig
7. Fire and gas system did not prevent hydrocarbon ignition

Blowout preventer did not seal the well
8. Blowout preventer (BOP) emergency mode did not seal well
Introduction

Technical Presentation
Well Integrity Was Not Established or Failed
After drilling to total depth, casing is run to bottom in preparation for the cement job. A double valve float collar is used to prevent backflow or ingress of fluids through the shoe track until the cement hardens and creates a permanent barrier.

April 18th 00:30 – April 19th 19:30

- Long string design robust, consistent with similar wells in the area
- 9 attempts made to establish circulation to convert float valves
- Circulate ~6 times open hole volume, limited circulation due to concerns over creating losses and hole washout
- No evidence that hydrocarbons entered the wellbore prior to the cementing operation
Cement is pumped down casing through the float collar and up the annulus to isolate the primary reservoir sands.

**April 19th 19:30 – April 20th 07:00**

- Nitrogen cement slurry chosen
  - To achieve light weight slurry due to limited pore pressure / fracture gradient window

- Possible risk
  - Stability of foam
  - Relatively small volume
  - Susceptible to contamination

- Mitigation of risk by
  - Thorough testing of slurry design
  - Precise placement

- Centralization
  - 6 inline centralizers spaced across the reservoir sands
  - Additional centralizers not run because incorrectly thought to be wrong type
  - Risk of channeling above reservoir sands known and accepted
**Key Finding #1**

The annulus cement barrier did not isolate the reservoir hydrocarbons.

- Foam slurry recommended was a complex design
- Risk of contamination using small volume of cement
- No fluid loss additives
- Incomplete pre-job cement lab testing
- Foam slurry was likely unstable and resulted in nitrogen breakout

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Cement is pumped down the landing string and casing into the annulus to isolate hydrocarbon bearing sands.
### Cement Slurry Design Issues

An independent lab completed over 500 tests on a representative cement slurry and reported the following:

- 50% quality foam at surface conditions was not stable
- 18.5% quality foam (downhole quality) was not stable
- Yield point of the Halliburton slurry was too low for the foam cement (2 lb / 100 ft² yield point at 135 deg F)
- Fluid loss for the base slurry was excessive compared to industry recommendations (302 cc versus 50 cc per 30 min)

Note: QUALITY = Nitrogen Volume / (Nitrogen + Base Slurry Volume)
Flow Through Shoe Track - Supporting Evidence

Casing Shoe Failure | Key Observations for Flow Through Shoe vs. Seal Assembly | Seal Assembly Failure
--- | --- | ---
Y | Mechanical Barrier Failure Mode Identified | Y
Y | Realistic Net Pay Assumption | N
Y | 1400 psi recorded on drill pipe during negative test at 18:30 | N
Y | Ability to flow from 20:58 | N
Y | Pressure Increase from 21:08 to 21:14 | N
Y | Pressure Response from 21:31 to 21:34 | N
Y | Timing for Gas Arrival to Surface | N
Y | Static Kill | N

Key Observations for Flow Through Shoe vs. Seal Assembly:

- Mechanical Barrier Failure Mode Identified
- Realistic Net Pay Assumption
- 1400 psi recorded on drill pipe during negative test at 18:30
- Ability to flow from 20:58
- Pressure Increase from 21:08 to 21:14
- Pressure Response from 21:31 to 21:34
- Timing for Gas Arrival to Surface
- Static Kill
Key Finding #2
The shoe track mechanical barriers did not isolate the hydrocarbons

- **Shoe track** had two types of mechanical barriers: cement in the shoe track and the double check valves in the float collar.
- **Shoe track** cement failed to act as a barrier due to contamination of the base slurry by break out of nitrogen from the foam slurry.
- Hydrocarbon influx was able to bypass the float collar check valves due to either:
  - Valves failed to convert or
  - Valves failed to seal
- Flow through shoe confirmed by fluid modeling and Macondo static kill data.

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*Tail cement is displaced down the casing into the shoe track. The tail cement is designed to prevent flow from the annulus into the casing. The float collar valves, which provide a second barrier, must close and seal to prevent flow up the casing.*

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**Diagram:**
- **Riser**
- **BOP**
- **Sea Floor**
- **Casing**
- **Retriever**
- **Shoe track cement**
- **Centralizers**
- **Check Valves**
- **Float Collar**
- **Flow Ports**
- **Hydrocarbon Flow Path**
Hydrocarbons Entered the Well
Undetected and Well Control Was Lost
A positive pressure test verifies the integrity of the casing and seal assembly.

April 20th 07:00 – 12:00

- Casing was pressure tested to:
  - 250 psi (low)
  - 2700 psi (high)
- Test successful
- Proved integrity of blind shear rams, seal assembly, casing and wiper plug
- Test does not test the shoe track due to presence of wiper plug
The negative-pressure test checks the integrity of the shoe track, casing and wellhead seal assembly. This simulates conditions during temporary abandonment when a portion of the well is displaced to seawater.

April 20th 15:04 – 19:55

- Negative test simulates underbalanced condition
- Spacer used between mud and seawater
- Leaking annular at start of test moved spacer across kill line inlet
- Negative test started on drill pipe but changed to kill line
- Bleed volumes higher than calculated
- Drill pipe built pressure to 1400 psi with no flow on the kill line
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Key Finding #3
The negative pressure test was accepted although well integrity had not been established

- Bleed volumes not recognized as a problem
- Anomalous pressure on drill pipe with no flow from kill line
- Test incorrectly accepted as successful
- Negative testing not standardized
Well Monitoring – Driller’s Console and Mudlogging unit

- Well monitoring is performed to understand if the well has losses or gains
- Driller is responsible for monitoring and shutting in the well
- The mudlogger provides monitoring support to the driller
- Displays and trending capability available in both Driller’s and Mudlogger’s cabins
- Flow, pressure and pit sensors can indicate flow
- Simultaneous activities were taking place on April 20th to prepare for rig move
- Standards for monitoring do not specifically address end-of-well activities
April 20th 19:55 – 21:14

- 20:02 Resume displacement of mud with seawater
- 20:52 Well becomes underbalanced and starts to flow
  - After 20:58 gain being taken and pressure begins increasing
    - Flow from well masked by emptying of trip tank
- 21:08 Pumping stops for sheen test
  - Pressure increases with pump off
- 21:14 Sheen test complete, displacement resumes
Key Finding #4
The influx was not recognized until hydrocarbons were in the riser

Flow indications:
- #1: Drill pipe pressure increased by 100 psi, (expected decreased); ~39 bbl gain from 20:58 to 21:08
Key Finding #4
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Flow indications:
- #1: Drill pipe pressure increased by 100 psi, (expected decreased); ~39 bbl gain from 20:58 to 21:08
- #2: Drill pipe pressure increased by 246 psi with pumps off
  - Flow out does not immediately drop after shutting down pump

Based on Real-time Data

Cumulative Gain

Flow Out (calibrated)
Flow In (rig pumps)
DP Press (rig pumps)

Decreasing trend should have continued

Indication #1

Indication #2

Overboard line opened Flow out available only to driller after 21:10

Normal Flow Back
Key Finding #4
The influx was not recognized until hydrocarbons were in the riser

Flow indications:
- #1: Drill pipe pressure increased by 100 psi, (expected decreased); ~39 bbl gain from 20:58 to 21:08
- #2: Drill pipe pressure increased by 246 psi with pumps off
  - Flow out does not immediately drop after shutting down pump
- #3: Drill pipe pressure increased by 556 psi with pumps off; ~300 bbl gain

No well control actions taken
Key Finding #5
Well control response actions failed to regain control of the well

Based on Real-time Data

- Attempt to bleed pressure
- Close Drill Pipe
- Pumps shut down
- Mud shoots up derrick
  - Diverter closed
  - BOP activated
- Discussion about “Differential Pressure”
- Mud overflowing onto rig floor
- Annular leaking
- Pressure increase due to annular activation

Explosion at 21:49

Influx enters riser

First indication of well control response: 49 minutes and 1000 bbls after initial influx

- Mud and water raining onto deck
- TP calls WSL, getting mud back, diverted to MGS, closed or was closing annular
- AD calls Senior TP, Well blowing out, TP is shutting it in now

Deepwater Horizon Accident Investigation
Hydrocarbons Ignited on the
Deepwater Horizon
When responding to a well control event the riser diverter is closed and fluids sent to either the mud gas separator or to the overboard diverter lines.

**Diversion to the MGS**
- Rig crew has the option to divert flow to port/starboard overboard lines or the MGS
- Diverting to port or starboard will result in fluids venting overboard
- Liquid outlet from MGS goes to the Mud System under the main deck
Deepwater Horizon Accident Investigation

Gas flow to Surface at high rate: 21:46 to 22:00

- Hydrocarbon flow from surface equipment
  - Instantaneous gas rates reached 165 mmscfd
  - Pressures exceeded operating ratings (above 100 psi)
  - Gas would probably have vented from:
    - Slip joint packer into the moon pool
    - 12” MGS “gooseneck” vent
    - 6” MGS vacuum breaker vent
    - 6” overboard line through burst disk
    - 10” mud line under the main deck

When responding to a well control event the riser diverter is closed and fluids sent to either the mud gas separator or to the overboard diverter lines.
Gas Dispersion across the Deepwater Horizon 21:46 to 21:50 hrs
Secondary protective systems did not prevent ignition

Secondary Protective Systems
- Gas cloud reached the supply air intakes for engine rooms 3, 4, 5 & 6
- The Fire and Gas system did not automatically trigger a shutdown of the HVAC system for the engine rooms
- Limited areas of the rig are designated as electrically classified zones

Secondary protective systems are designed to reduce the potential consequence of an event once the primary protective systems have failed.
Key Finding #6
Diversion to the mud gas separator resulted in gas venting onto the rig

When responding to a well control event the riser diverter is closed and fluids are sent to either the mud gas separator or to the overboard diverter lines.

- Hydrocarbons were routed to the mud gas separator instead of diverting overboard
- Resulted in rapid gas dispersion across the rig through the MGS vents and mud system

BOP
Sealed at 21:47
Key Finding #7
The fire and gas system did not prevent hydrocarbon ignition

- Gas dispersion beyond electrically classified areas
- Gas ingress into engine rooms via main deck air intakes
- The on-line engines were one potential source of ignition
Emergency Well Control System Did Not Seal the Well
Blowout Preventer (BOP)

Emergency Methods of BOP Operation Available on DW Horizon

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<thead>
<tr>
<th>Method</th>
<th>Manual</th>
<th>Automatic</th>
<th>ROV Intervention</th>
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Deepwater Horizon Accident Investigation
BOP Response (Before the Explosions)

April 20th
- 21:38 – Hydrocarbons enter the riser
- Activation of Lower Annular BOP

BOP is designed to seal the wellbore and shear casing or drill pipe if necessary.

April 20th
- 21:41 annular BOP closed but appears not to have sealed the annulus
- 21:47 a VBR likely closed and sealed the annulus

Deepwater Horizon Accident Investigation
BOP Response (Impact of Explosions)

April 20th

- Damage to MUX cables and hydraulic line
  - Opening of annular BOP

- Rig drifted off location
  - Upward movement of the drill pipe in the BOP

MUX cables provide electronic communication and electrical power to the BOP control pods.
BOP Response (After the Explosions)

There are several emergency methods of activating the BSR to seal the well.

April 20th
- EDS attempts failed to activate BSR
- AMF sequence likely failed to activate BSR

April 21st – 22nd
- ROV hot stab attempts to close BOP were ineffective
- ROV simulated AMF function likely failed to activate BSR
- ROV activated auto-shear appears to have activated but did not seal the well

April 25th – May 5th
- Further ROV attempts using seabed deployed accumulators were unsuccessful
Key Finding #8
The BOP emergency mode did not seal the well

Explosions & Fire:
Loss of communication
Loss of electrical power
Loss of hydraulics

- EDS function was inoperable due to damage to MUX cables
- AMF could not activate the BSR due to defects in both control pods
- Auto-shear appears to have activated the BSR but did not seal the well
- Potential weaknesses found in the BOP testing regime and maintenance management systems

The AMF provides an automatic means of closing the BSR without crew intervention.

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Summary of Findings and Recommendations
Recommendations

25 Recommendations Specific to the 8 Key Findings

BP Drilling Operating Practice and Management Systems
- Engineering Technical Practices and Procedures
- Further Enhance Deepwater Capability and Proficiency
- Strengthen Rig Audit Action Closeout and Verification
- Introduce Integrity Performance Management for Drilling and Wells Activities

Contractor and Service Provider Oversight and Assurance
- Cementing Services
- Drilling Contractor Well Control Practices and Proficiency
- Oversight of Rig Safety Critical Equipment
- BOP Configuration and Capability
- BOP Minimum Criteria for Testing, Maintenance, System Modifications and Performance Reliability

BP has accepted all the recommendations and is reviewing how best to implement across its world wide operations
Summary of Key Findings

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