DET NORSKE VERITAS

Addendum to Final Report for UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF OCEAN ENERGY MANAGEMENT,
REGULATION, AND ENFORCEMENT
WASHINGTON, DC 20240

FORENSIC EXAMINATION OF DEEPWATER HORIZON BLOWOUT PREVENTER

CONTRACT AWARD NO. M10PX00335

Report No. EP030842
30 April 2011

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Forensic Examination of Deepwater Horizon Blowout Preventer

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List of Abbreviations and Acronyms

AMF	Automated Mode Function
API	American Petroleum Institute
BOEMRE	Bureau of Ocean Energy Management, Regulation, and Enforcement
BOP	Blowout Preventer
BP	BP Exploration & Production Inc.
BSR	Blind Shear Ram
CAD	Computer Aided Design
CSR	Casing Shear Ram
DHS	Department of Homeland Security
DNV	Det Norske Veritas
DOI	Department of the Interior
EDS	Emergency Disconnect Sequence
EPA	Environmental Protection Agency
ERT	Evidence Response Team
FAT	Factory Acceptance Test
FBI	Federal Bureau of Investigation
FEA	Finite Element Analysis
HP	High Pressure
HPU	Hydraulic Pressure Unit
ID	Inside Diameter
JIT	Joint Investigation Team
LA	Lower Annular
LMRP	Lower Marine Riser Package
MIC	Microbiologically Influenced Corrosion
MMS	Minerals Management Service
MODU	Mobile Offshore Drilling Unit
MOEX	Mitsui Oil and Exploration Company
MUX	Multiplex cables
NACE	National Association of Corrosion Engineers
NASA	National Aeronautics and Space Administration
NPT	National Pipe Thread
OD	Outside Diameter
PBOF	Pressure Balance of Oil Filled
PETU	Portable Electronic Test Unit
PSIG	Pounds Per Square Inch Gauge
RCB	Rigid Conduit Box cable
ROV	Remotely Operated Vehicle
SCAT	Systematic Causal Analysis Technique
SEM	Subsea Electronic Modules
SMYS	Specified Minimum Yield Strength

STM	Subsea Transducer Module
TWG	Technical Working Group
UA	Upper Annular
USCG	United States Coast Guard
UTS	Ultimate Tensile Strength
VBR	Variable Bore Ram
YS	Yield Stress

1 INTRODUCTION

A Joint Investigation Team (JIT) of the Departments of the Interior (DOI) and Homeland Security (DHS) was charged with investigating the explosion, loss of life, and blowout associated with the Deepwater Horizon drilling rig failure. As a part of this overall investigation, Det Norske Veritas (DNV) was retained to undertake a forensic examination, investigation, testing and scientific evaluation of the blowout preventer stack (BOP), its components and associated equipment used by the Deepwater Horizon drilling operation.

Forensic testing was completed on March 4, 2011. A final forensic investigation report titled "Forensic Examination of Deepwater Horizon Blowout Preventer - Volume I Final Report" [Report No. EP030842] was issued on March 20, 2011.

As a follow on to the Final Report, this addendum provides:

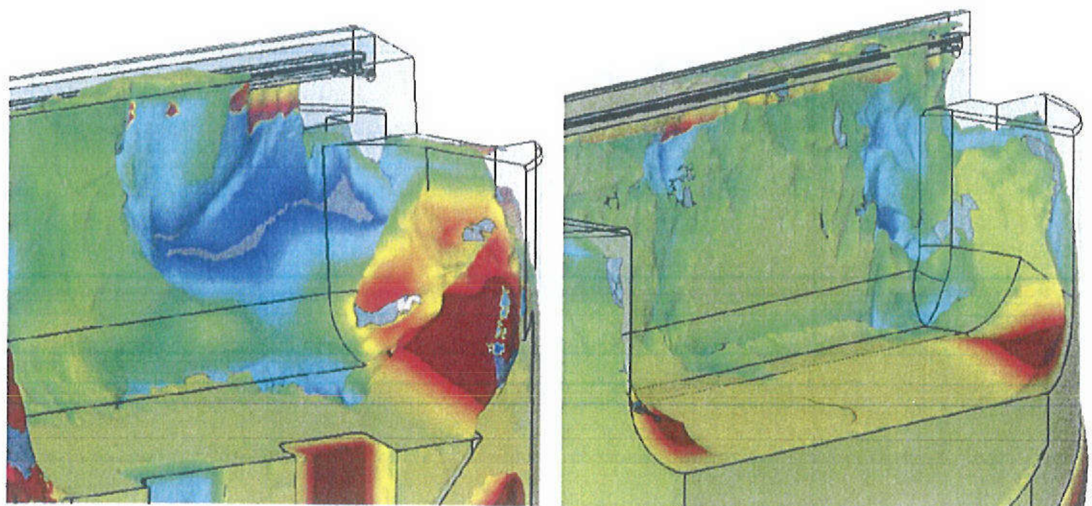
- Corrections to text
- Clarifications requested by BOEMRE
  - Fault Tree Analysis
  - Alternative theories
  - Cutting (or not) of Upper VBR hoses via ROV
  - Support for elastic buckling theory
- An update of the off-center drill pipe finite element analysis (FEA) model
- Revised figures and updated text for DNV Forensic Report starting at Page 156 directly following Figure 133

2 REPORT SUPPLEMENTS

2.1 Corrections to Text

- Page 2 – Section 1.2 – First Paragraph – Line 1:
  - Substitute "allowing hydrocarbons to reach the Deepwater Horizon"
  - In place of "allowing hydrocarbons to enter the drilling riser and reach the Deepwater Horizon"
- Page 4 – Section 1.4 – Third Paragraph – Line 6:
  - Substitute "A drill pipe tool joint located between the Upper Annular and the Upper VBRs was pushed into the lower portion of the Upper Annular during well control activities or by forces from the well blowout. This created a fixed point at the Upper Annular arresting further upward movement of the drill pipe. The drill pipe was radially constrained but able to move vertically at the Upper VBRs. The most likely scenario is that forces from the blowout of the well induced a buckling condition on the portion of drill pipe between the Upper Annular and Upper VBRs."
  - In place of "A drill pipe tool joint was located between the Upper Annular and the Upper VBRs. With both the Upper Annular and the Upper VBRs closed on the drill pipe, forces from the flow of the well pushed the tool joint into the Upper Annular element. This created a fixed point arresting further upward movement of the drill pipe. The drill pipe was then fixed but able to pivot at the Upper Annular, and horizontally constrained but able to move vertically at the Upper VBRs. Forces from the flow of the well induced a buckling condition on the portion of drill pipe between the Upper Annular and Upper VBRs."
- Page 7 – Section 1.6.6 – First Paragraph – Line 2:
  - Substitute "BOP components"
  - In place of "ROV components"
- Page 23 – Section 5.7 – Third Paragraph – Line 1:
  - Substitute "removed from seven of the recovered drill pipe segments"
  - In place of "removed from each recovered drill pipe segment"
- Page 24 – Section 5.9 – Second Paragraph – Line 1:
  - Substitute "reviewed with three objectives:"
  - In place of "reviewed with two objectives:"
- Page 34 – Section 6.1.7.2.2 – Third Paragraph – Line 1:
  - After first sentence add "Table 3 presents data for two operations. One operation was the pressures that were applied to open the ram bonnets (the two columns of Starboard and Port CLOSE). The other operation was applying pressure to retract and remove the rams (the two columns of Starboard and Port OPEN)."

- Page 76:
  - Substitute "Revised Figure 34 (b) Bottom View – Kill Side and 34 (c) Top View – Choke Side" (below)
  - In place of "Figure 34(c) Bottom View – Kill Side and 34 (d) Top View – Choke Side"
  - Note: Revised Figure 34 represents revised CAD geometry for the lower BSR block supplied by Cameron on March 31, 2011.



(b) Bottom – Kill Side **(c) Top View – Choke Side**

Revised Figure 34 Three-Dimensional Laser Scan of Port-Side (Lower) BSR Block

- Page 79 – Section 6.2.3.1 – Table 17 – Description Entry for Item No. 94:
  - Substitute "Recovered from the BOP on the Q-4000 between the BSR and CSR"
  - In place of "Recovered from the BOP at the Michoud Facility between the BSR and CSR"
- Page 98 – First Paragraph following Figure 59 – Line 5:
  - Substitute "is missing"
  - In place of "may be missing"
- Page 99 – First Paragraph – Line 3:
  - Add the following after the last sentence "The vertical "cuts" of the notches (corners) (Figure 60 and Figure 61) of the top and bottom drill pipe sections correspond respectively to (1) the tight tolerance between the BSR upper ram block top face and the opposite relief cavity of the lower ram block (sharp vertical cut of the notch on the top drill pipe – 83-B) and (2) the larger gap between the BSR upper ram block bottom face and the opposite relief cavity of the lower ram block (more deformation and tearing of the vertical cut of the notch on the bottom drill pipe – 94-B).

- Page 113 – Section 6.2.8.1 – Table 19 – Item No. 94-Q is repeated twice:
  - Delete one of the rows for Item No. 94-Q
- Page 153 – Section 6.5.2 – Third Paragraph – Line 2:
  - Substitute "These force components depend on the reservoir pressure and temperature, the fluid media in the drill pipe, the flow in the drill pipe, the friction between the fluid media and drill pipe and other factors."
  - In place of "These force components depend on the reservoir pressure, the fluid media in the drill pipe, the flow in the drill pipe, the friction between the fluid media and drill pipe and other factors."
- Page 154 – Bullet list at top of page:
  - Add additional bullet "Force due to thermal expansion of pipe between UA and BSR"
- Page 172 – Last Paragraph – Line 5:
  - Substitute "A Factory Acceptance Test and AMF/Deadman test was performed on what was noted in the report of those tests as the Blue Pod in June 2009. On receipt of the Control Pods at the NASA-Michoud facility the identification numbers found on the Subsea Electronic Module for the Yellow Control Pod matched the identification numbers recorded in the June 2009 test report for the Blue Control Pod. The review of available records could not confirm the date when the Subsea Electronic Module as mounted in the Blue Pod AMF/Deadman last underwent a Factory Acceptance Test. To discern the state of the AMF/Deadman it is necessary to undertake further examination, investigation and tests of the Subsea Electronic Modules of both the Yellow and Blue Control Pods."
  - In place of "A Factory Acceptance Test and AMF/Deadman test was performed on the Blue Pod in June 2009. The review of available records could not confirm the date when the Yellow Pod AMF/Deadman last underwent an AMF/Deadman Test."
- Page 174 – First Paragraph – Line 4:
  - Substitute "A drill pipe tool joint located between the Upper Annular and the Upper VBRs was pushed into the lower portion of the Upper Annular during well control activities or by forces from the well blowout. This created a fixed point at the Upper Annular arresting further upward movement of the drill pipe. The drill pipe was radially constrained but able to move vertically at the Upper VBRs. The most likely scenario is that forces from the blowout of the well induced a buckling condition on the portion of drill pipe between the Upper Annular and Upper VBRs."
  - In place of "A drill pipe tool joint was located between the Upper Annular and the Upper VBRs. With both the Upper Annular and the Upper VBRs closed on the drill pipe, forces from the flow of the well pushed the tool joint into the Upper Annular element. This created a fixed point arresting further upward movement of the drill pipe. The drill pipe was then fixed but able to pivot at the Upper Annular,

and horizontally constrained but able to move vertically at the Upper VBRs. Forces from the flow of the well induced a buckling condition on the portion of drill pipe between the Upper Annular and Upper VBRs."

- Page 175 – Section 7.3.4 – Second Paragraph – Line 1:
  - Substitute "On loss of well control the drill pipe downhole of the Upper Annular was subjected to vertical forces from the blowout."
  - In place of "On loss of well control the drill pipe downhole of the Upper Annular was subjected to vertical forces from the flow of well fluids."
- Page 176 – Section 7.3.7 – Second Paragraph – Line 1:
  - Substitute "The most likely scenario is that forces from the blowout induced a buckling condition on the portion of drill pipe between the fixed point (vertical) of the Upper Annular and Upper VBRs (horizontal constraint)."
  - In place of "Forces from the flow of the well downhole of the VBRs induced a buckling condition on the portion of drill pipe between the fixed point (vertical) of the Upper Annular and Upper VBRs (horizontal constraint)."
- Page 178 – Section 8.1.6 – First Paragraph – Line 2:
  - Substitute "BOP components"
  - In place of "ROV components"

2.2 Clarifications Requested by BOEMRE

2.2.1 Fault Tree Analysis

DNV provides the following clarification of the fault tree analysis for off-center drill pipe at the location of the BSR and consistent with the timing of possible activation of the BSR.

Alternate theories for what could have caused the drill pipe to be off-center when the BSRs closed were considered. A fault tree approach was used which requires the listing of conditions necessary to satisfy or allow a fault to occur. In this case the 'fault' is defined as the cause or contributing factors for the drill pipe to be off-center. The theories (faults) and conditions necessary are outlined below and illustrated in Figure A.

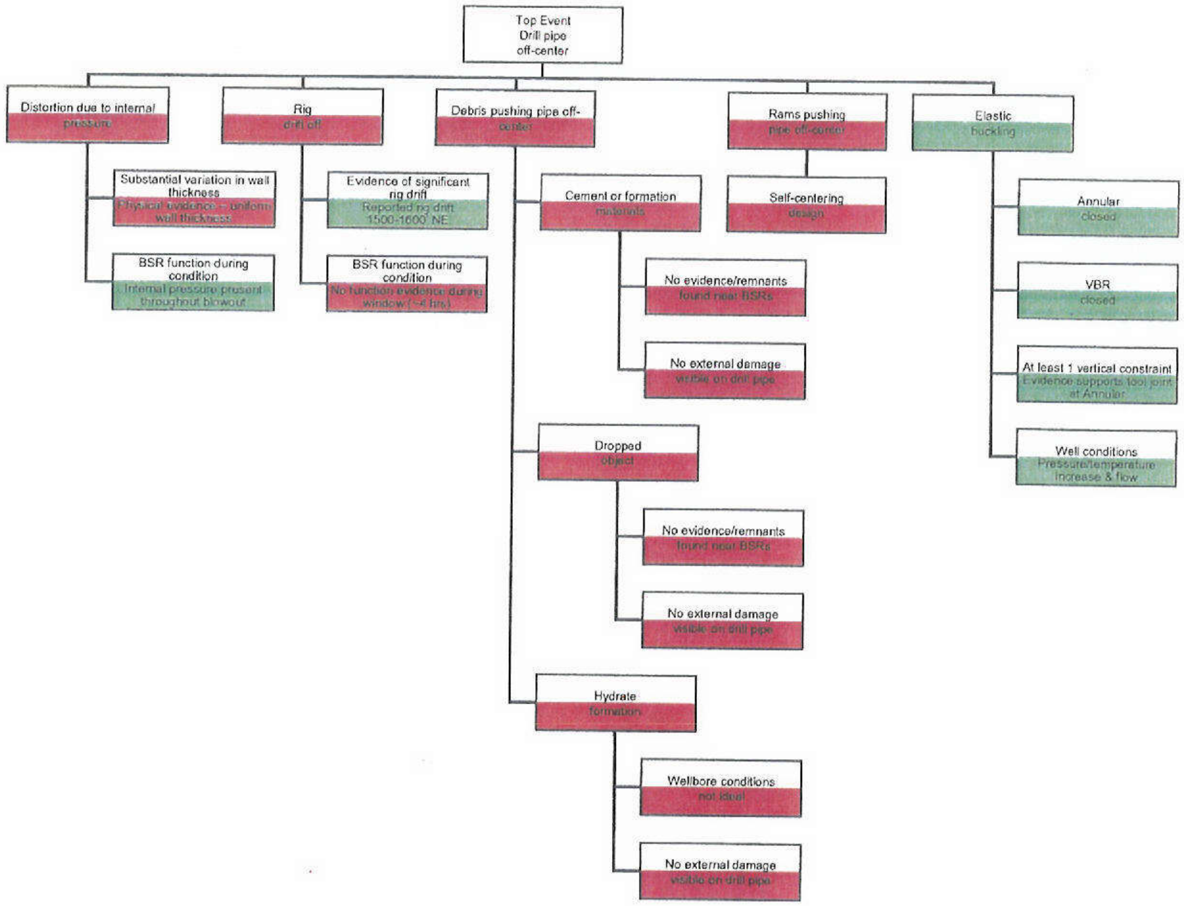


Figure A Fault Tree for Drill Pipe Off-Center

2.2.1.1 Pipe distortion or bowing from internal pressure

Conditions necessary for this to occur were determined to be a substantial variation in the wall thickness of the drill pipe. This would result in a thinner wall on one side of the pipe which could then cause the pipe to distort under internal pressure. This fault was ruled out as credible due to the lack of physical evidence to support the wall variation. The examinations of the drill pipe carried out at the NASA-Michoud facility and at the DNV Materials and Corrosion Technology Center in Columbus, Ohio, found the walls to be of a uniform thickness.

2.2.1.2 Rig drift off

It is most likely that with the tool-joint against the Upper Annular, any bending or flexing of the drill pipe between the Upper Annular and the Upper VBR would be off-center to the side of the wellbore in the opposite direction of the rig drift. This fault was ruled out as credible, because the physical evidence is that the pipe was trapped off-center to the kill side of the wellbore, which was oriented to the north; while the rig was reported to have drifted to the northeast. In this scenario, this northeast rig drift would have moved the pipe off-center to the choke side of the BSRs, oriented to the south, and opposite the kill side where the pipe was trapped.

A more complex scenario would be for a bending moment to be induced on the pipe with the drift of the rig in the same direction that the pipe was found within the wellbore to be off-center. This scenario would include a more complex means of loading and transfer of forces. It can not be ruled out that with one or both annulars closed such a scenario may be possible. However, this is believed to be unlikely due to the stiffening (straightening) effect that each of the closed annulars would have on the drill pipe. It should be noted that the Lower Annular was found in an open position; placing in question the Lower Annular's role in this scenario. DNV is unaware of any evidence that the Lower Annular was actuated open following activation of the BSR, although the possibility exists. If the Lower Annular was closed and hydraulic pressure was lost, the Lower Annular may have relaxed and opened, providing for the possibility that the Lower Annular was previously closed.

Further, for the rig drift off scenario to be credible, the BSRs would have had to function while the rig had drifted from above the wellbore, thereby forcing the drill pipe below the annulars off-center. Without the BSRs functioning during this period, it is not possible to explain the physical evidence of the drill pipe (i.e. the drill pipe was off-center when the BSR sheared the pipe). From the timeline (Appendix F of the Forensic Report) the rig drift was reported at 1500' to 1600' between 03:27 to 03:29 on 21 April 2010. At less than 4 hours later (07:06 on 21 April 2010) it was reported that the rig appeared to have returned to its original position. During that time span there were no ROV intervention activities on the BSRs. The only function that could have occurred while the rig was drifted off position would be a spurious activation during this time of the AMF/Deadman function. There is no evidence to support that conditions necessary for the AMF/Deadman to function would have occurred during this time window.

In summary, the scenario that rig drift caused or contributed to the drill pipe being off-center was not ruled out completely, but it is not viewed as very likely based on the above considerations.

2.2.1.3 Debris pushing the pipe off-center

Conditions that could contribute to this possibility were cement or formation materials, a dropped object from the rig, or a large hydrate formation from well flow. No evidence of external damage on the drill pipe was observed that could be attributed to cement, other debris or a dropped object that would result in pushing the pipe off-center. No remnants of cement or formation materials were found near the BSRs, but with the flow that occurred these remnants would probably not be expected. Concerning hydrates, no evidence or remnants would have been expected, however, conditions were not ideal for hydrate formation at the time of the incident, and hydrate build-up would have taken the path of least resistance, building vertically up the drill pipe rather than building horizontally and exerting a lateral force. None of the conditions could be substantiated, and so this fault was ruled as not being credible.

2.2.1.4 Ram (BSRs) pushes drill pipe off-center

This fault was determined as not being credible because the design of the rams was to be self-centering.

2.2.1.5 Elastic Buckling

This fault was carried forward as credible and further analysis was performed in support of it per the Forensic Report.

2.2.2 Alternative Theories

2.2.2.1 Possibility that the buckling force could have been generated from the compressive force of the weight of the drill pipe after the block fell to the rig floor

It is common drilling practice or rule to remove suspended loads as soon as practicable. Therefore, while the drill pipe was suspended in the derrick, the drill pipe would have been set in slips to remove the suspended load from the derrick or travelling block. This would have kept the drill pipe position stable, especially with regard to the tool joint position in the BOP. Additionally, in order for the compression load to have created a buckling load in the vicinity of the BSRs, a hard stop would have been necessary below the BSRs such as the Variable Bore Rams (VBRs). From the drill pipe evidence recovered, the tool joint was positioned at the bottom of the Upper Annular and not located near or trapped by the VBRs. It was not considered likely that the gripping force of the closed VBRs would have been sufficient to hold the compressive load necessary to buckle the pipe.

DNV can not rule out that compressive loads from the weight of the drill pipe above the BOP may have contributed to the elastic buckling scenario. However for this to occur, the drill pipe would have to be pinned (no vertical movement) at some point below the BSR.

2.2.2.2 Possibility that the buckling force could have been generated from temperature, pressure, flow and debris states at the time

DNV has previously discussed in the fault tree analysis above how pressure and debris were considered and determined not credible as a force to independently cause the pipe to move off center within the wellbore. The issue of flow and pressure as components to elastic buckling during well blowout is addressed within the Forensic Report. Temperature (thermal expansion) was also mentioned as a possible contributor to buckling but not discussed in detail. The constraint conditions for buckling due to thermal expansion were more rigorous, namely that the drill pipe had to be fixed at both ends for forces to develop. As discussed in the Forensic Report, while the tool joint would have been one fixed point, the VBRs only constrained the drill pipe radially not vertically. However, it is likely that some degree of friction is associated with drill pipe movement through the VBRs. This resistance to movement (or any other resistance to movement) within the VBRs allows for the possibility for thermal expansion forces to contribute to the buckling forces.

2.2.2.3 Possibility that the non-closure of the BSR blocks could have been caused by an inconsistent Solenoid valve 103Y or in an under-powered manner

The possibility of BSR closure through an alternate close function other than the high pressure circuit was considered and is included in the fault tree listed in Appendix G of the Forensic Report (located on the left side of the fault tree diagram). The activation of the BSR Close Function from either the Toolpusher's Control Panel or the Driller's Control Panel was ruled as not credible. There was no evidence (i.e., no eyewitness or witnesses of fact evidence) to substantiate either intentional selection or accidental selection of the 'normal' blind shear ram close function from surface. The layout of the control panel is such that the 'normal' BSR function is not in close proximity to other intentional functions. Further, the evidence provided to the JIT by Mr. Pleasant was that on arrival on the bridge at approximately 21:56 (20 April 2010), the BSRs were in an 'open' state. The only function activated after that time and before the rig was abandoned was the pushing of the Emergency Disconnect Sequence, which would have functioned the high-pressure (4,000 psi) circuit.

The high pressure circuit was examined and tested during the forensic investigation. Testing determined that the 8 x 80 gallon accumulators functioned as intended in the as-received condition. The scenario as best as DNV was able to determine from the investigation is that the upper VBRs were closed prior to the full loss of well control restricting well flow to the inside of the drill pipe. If for whatever reason the AMF/Deadman partially functioned but did not fully deploy the BSRs and did not result in shearing the pipe, the ram blocks would not have been exposed to erosive flow. The Autoshear function (being totally independent of the intermittent solenoid) would have fully closed the BSR. Analysis of the hydraulic fluid collected from the port side close operator of the BSR substantiated activation either by the Authoshear or possibly the

AMF/Deadman functions, not through ROV intervention (pg. 167 - DNV Forensic Report).

2.2.2.4 Possibility that the non-closure of the BSR blocks could have been caused by pressure being applied to the BOP and then relieved ("double clutching")

A connection cannot be made between alternating applied and relieved closing pressure to the BSRs and the extent of the erosive damage found. The ST Lock system is designed to allow minimal reverse movement if hydraulic pressure is relieved. The overall contribution of this "double clutching" phenomenon cannot in DNV's opinion be of significance compared to the contribution of the trapped pipe between the ram blocks. Those ROV interventions which were deemed in DNV's opinion to be successful in applying pressure (build up of pressure, but no fluid flow) all occurred after the Autoshear function was activated by shearing the pin at approximately 07:30 on 22 April 2010. Thus the significant event which had the largest contribution to erosion and degradation of the sealing function was the off-center pipe trapped between the ram blocks.

2.2.3 Cutting (or not) of Upper VBR Hoses via ROV

All hoses that were cut as part of the ROV interventions were documented on and included in Appendix B (page 90) of the DNV Forensic Report. As can be seen from that drawing, while the hose to the Middle VBR was cut as part of the ROV interventions, the hoses to the Upper VBR were found to be intact (i.e. not cut).

2.2.4 Support for Elastic Buckling Theory Requested by BOEMRE

2.2.4.1 Elastic Buckling

Elastic buckling is a well-known phenomenon which is part of basic courses in structural or mechanical engineering. Elastic buckling is a failure mode of a structural element which loses stability. Elastic buckling of a slender column was mathematically modeled in 1757 by the Swiss mathematician Leonhard Euler who derived a closed form formula for the maximum axial load that a long, slender, ideal column can carry without buckling.

Elastic buckling is characterized by the fact that the structural element reverts to its original form once the force causing the buckling is removed. An everyday example of buckling is what can be observed if a thin plastic ruler is compressed gradually from each end and the ruler then bends due to this compressive force. Once the force is relieved, the ruler returns to its original form.

Plastic buckling is a similar mechanism to elastic buckling with the difference, however, that the plastic buckling results in permanent deformations such that the structural element does not return to its original form but remains deformed once the force causing the buckling is removed.

Elastic buckling is a phenomenon that exists for different slender structural elements, such as columns, plates, shells and pipelines. A classical text book on elastic buckling is:

- Stephen P. Timoshenko, Professor at Stanford University, California: *Theory of Elastic Stability*, McGraw-Hill Book Company, 1936.

There exists many textbook and research papers on the topic.

2.2.4.2 Buckling in Drilling

Elastic buckling is a well-known phenomenon – and problem – within drilling. During drilling the long and slender drill pipe is exposed to a compressive, downward force that can cause the drill pipe to buckle and thereby cause damage to the well casing. A particular buckling phenomenon during drilling is helical buckling where the drill pipe buckles into a spiral form. Much research has been devoted to find drilling equipment and methods that minimize the risk of buckling.

DNV has located no references in the literature to the buckling behavior of the drill string during a loss of well control. In such a situation the slender drill pipe is exposed to upward forces (e.g. from reservoir pressure and temperature, buoyancy, and flow forces) instead of being exposed to downward forces. As opposed to the normal drilling situation, where the operation is monitored and controlled, the situation is different during a loss of well control, where little or no information concerning the behavior of the drill pipe is gathered.

2.3 An Update of the Off-Center Drill Pipe Shearing Finite Element Analysis (FEA) Model

The conclusion of the forensic investigation that the primary cause required the drill pipe to be off-center is based on the physical evidence of the drill pipe, wellbore, and the BSR blocks and not the FEA model. The purpose of the model was to illustrate the difference between the BSR cutting a centered pipe versus an off-center pipe. The results of the FEA model supported the conclusions based on the physical evidence.

A revised Finite Element Analysis (FEA) model was performed and is summarized below. The revised model clarified the following issues:

1. Included latest Cameron CAD geometry for the lower BSR block, which was provided to DNV by Cameron on March 31, 2011, after DNV had issued the Final Report on March 20, 2011.
2. Included the constraints of the wellbore in the FEA model.
3. Provided allowance for the compressibility of the side packers in the Ram geometry.
4. Positioned the pipe initially with an offset of 0.5 inch from the side of the wellbore.

Ad 1: The CAD files originally provided by Cameron for the lower BSR block reflected geometry different from the lower BSR block recovered from the Deepwater Horizon BOP. Cameron discovered this and provided the updated CAD file for the Lower BSR block on March 31, 2011. The primary difference noted between the CAD files for the two BSR blocks was the size of the opening of the relief cavity on the top side of the lower BSR block. A comparison between the original and revised versions is given in the Figure B, with the updated lower BSR block geometry shown in red. The cavity opening was measured as 15.38 inches in the updated lower BSR block, compared to 16.875 inches for the originally provided lower BSR block CAD geometry. The revised FEA model used the updated lower BSR block geometry.

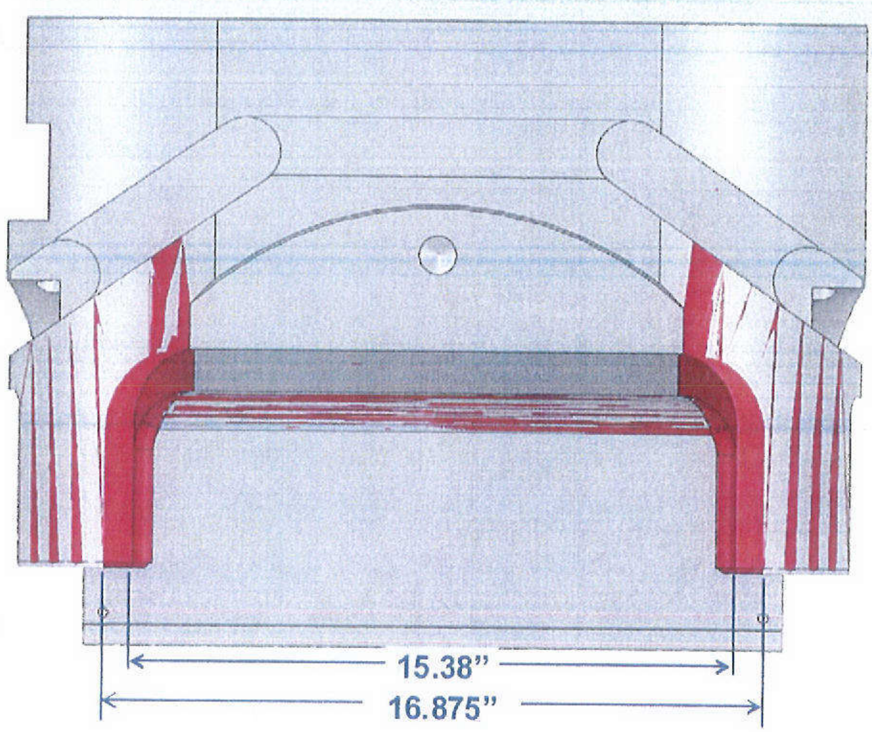


Figure B Comparison of the original CAD file compared to the updated CAD file for the Lower BSR block (red) provided on March 31, 2011

Ad 2: The results from the original BSR FEA model for shearing off-center drill pipe showed the drill pipe to be deformed into space where the wellbore wall would have been. In the revised FEA model, the geometrical constraint of the wellbore was included in the model.

Ad 3: In the original FEA model, the front faces of the side packers were included based on their geometry. While this is geometrically accurate, the elastomeric side packers are able to compress and would provide a relatively low level of resistance to closing of the BSR blocks. In the revised FEA model, the surfaces representing the side packer faces were made flush with the BSR block faces, thereby providing for the compressibility of the side packers.

Ad 4: The buckling model of the drill pipe predicted the drill pipe contacts the wellbore above the BSR cavity, see Figures 128 and 129 in the DNV Forensic Report. The curvature of the drill pipe as it crosses the BSR cavity places the pipe approximately 0.5 inches from the inside surface of the wellbore. For the revised FEA model for shearing off-center pipe, the drill pipe was offset from the inside wall of the wellbore by 0.5 inches.

With the above described modifications to the model, the results are summarized below.

For the updated model, the wellbore constrains the drill pipe from moving as far into the BSR cavity as in the original model; however, the drill pipe is still caught between the BSR block faces which prevents the BSR from fully closing. Even more important, the updated lower BSR block geometry reduces the clearance between the top blade of upper BSR block and the opposite relief cavity on the lower BSR block. With the previous geometry used in the original FEA model, there was room for the drill pipe to deform between the BSR blocks, but for the updated model there is limited clearance between these edges which further limits the ability of the BSR blocks to close.

During the shearing process, the forces (and equivalent pressures) increase to a maximum force during the shearing of the drill pipe followed by a decrease in force as the shearing proceeds. For the off-centered drill pipe, this decrease in force continues until the blocks close sufficiently to trap the drill pipe outside the shearing blade surfaces. As the trapped drill pipe further deforms, the forces increase rapidly with further displacement of the BSR blocks. The model can continue to increase the force applied to the rams to very large values; where the BOP operation is limited to the available hydraulic pressure. To report realistic final displacement, a final model force was selected as near to (but greater than) the equivalent available hydraulic pressure as the model captures.

The original FEA model predicted a 2-inch block displacement between the upper and lower BSR blocks for an applied force (model output RF_{MAX} in Figures 139 and 140 of the DNV Forensic Report) of 1,017,040 lb_f (equivalent to 4,273 psi of hydraulic pressure on the operator) with off-centered drill pipe trapped between the faces of the BSR blocks

(Ref pages 161 & 164 of the DNV Forensic Report). The revised FEA model predicted a 2.8-inch block displacement between the upper and lower BSR blocks for an applied force (RF_{MAX}) of 1,256,750 lb_f (equivalent to 5,280 psi) see last frame in revised Figures 139 and 140. The BSR would likely stall prior to the application of 5,280 psi, as the required pressure exceeds the available hydraulic system pressure (regulated to 4,000 psig), but the value of 5,280 psi was the model output closest to and not less than 4,000 psi. For comparison, the force in the prior frame is 440,646 lb_f which is equivalent to 1,851 psi. At this point, the force is rapidly increasing with little additional displacement of the BSR blocks due to the drill pipe deformation outside of the cutting surface of the BSR blades.

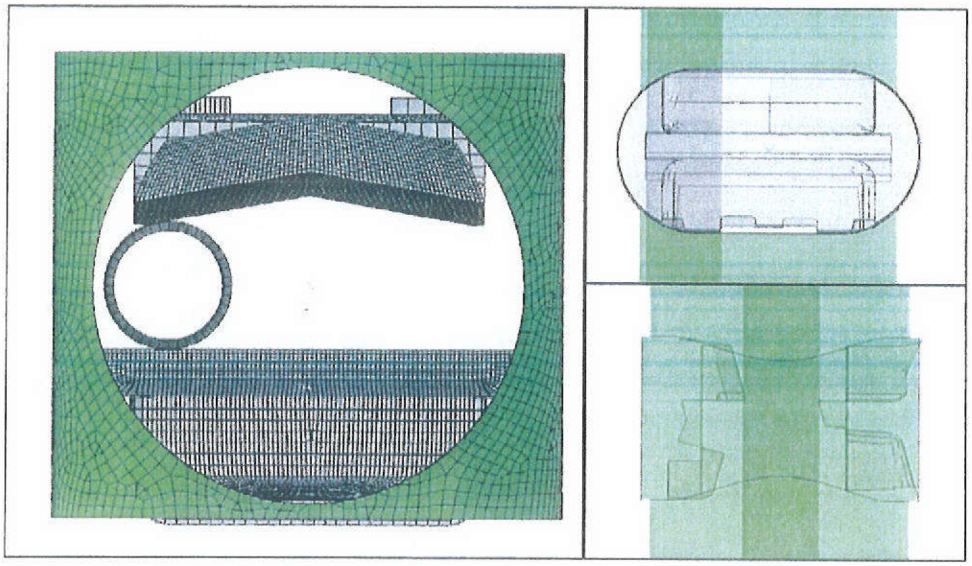
For the revised FEA model and with an applied equivalent pressure of 5,280 psi (which is greater than the available hydraulic pressure), the upper and lower BSR blocks were 2.8 inches from being fully closed (Revised Figures 146 and 148). The side packers were 1.7 inches from making initial contact and sealing. The lower BSR blade was 2.2 inches from contacting the rear packers and sealing.

In summary, the simulations undertaken with the revised geometry of the blind shear rams and the constraint of the wellbore on the position of the drill pipe do not change DNV's conclusions as stated in the DNV Forensic Report. In fact, the revisions result in findings that indicate the Blind Shear Rams would likely have 'stalled' further apart than in the original modeling (i.e. a 2.8 inch standoff versus a 2 inch standoff as noted in Figure 146 [pg 164]).

DNV closes this section as it began: the conclusion that the primary cause for the Blind Shear Rams failing to close and seal is based on the physical evidence, i.e., the physical state of the drill pipe and BSR blocks. The results of the modeling support and help explain the actual physical damage found on the drill pipe, blind shear rams and the kill side of the wellbore. The modeling also illustrated the difference between the BSR cutting centered drill pipe versus the drill pipe being off-center. However, one does not need to perform the modeling study to reach the key conclusion.

2.4 Revised Figures and Updated Text for DNV Forensic Report starting at Page 156 directly following Figure 133

- Page 156 – Paragraph directly following Figure 133 – Line 2:
  - Substitute "(displaced 0.5 inches from the inside wall of the wellbore as illustrated in Figure 134)."
  - In place of "(displaced to the far side of the wellbore as illustrated in Figure 134).
- Page 156:
  - Substitute Revised Figure 134
  - In place of Figure 134



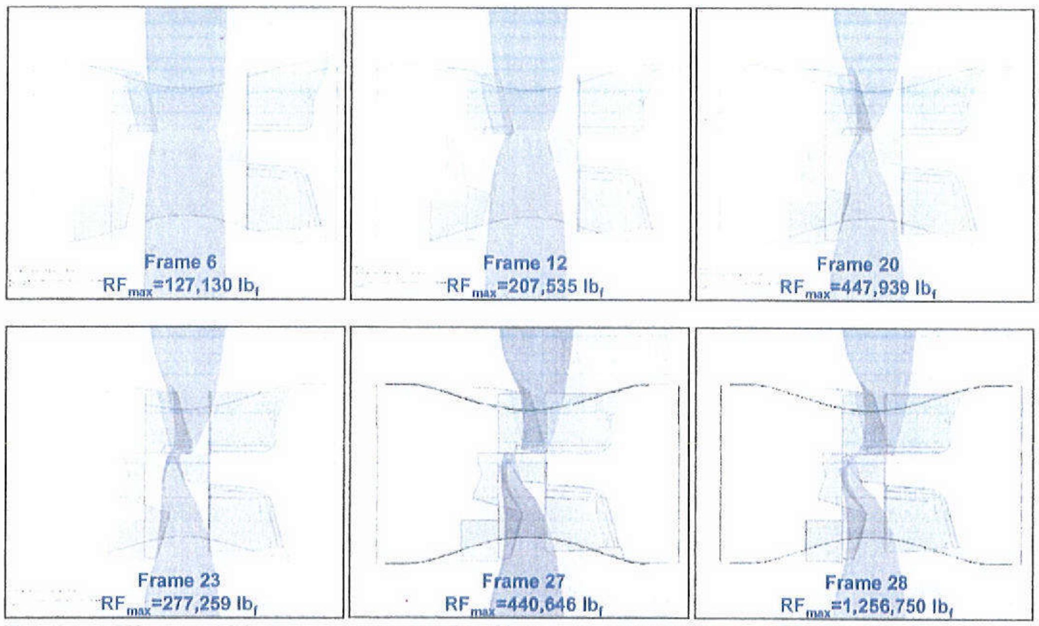
Revised Figure 134 FEA Model of BSR Blade Surfaces and Off-Center Drill Pipe

- Page 160 – Starting with paragraph directly below Figure 138 and continuing through Page 165 and stopping with the replacement of Figure 148:
  - Substitute all text and figures with the following:

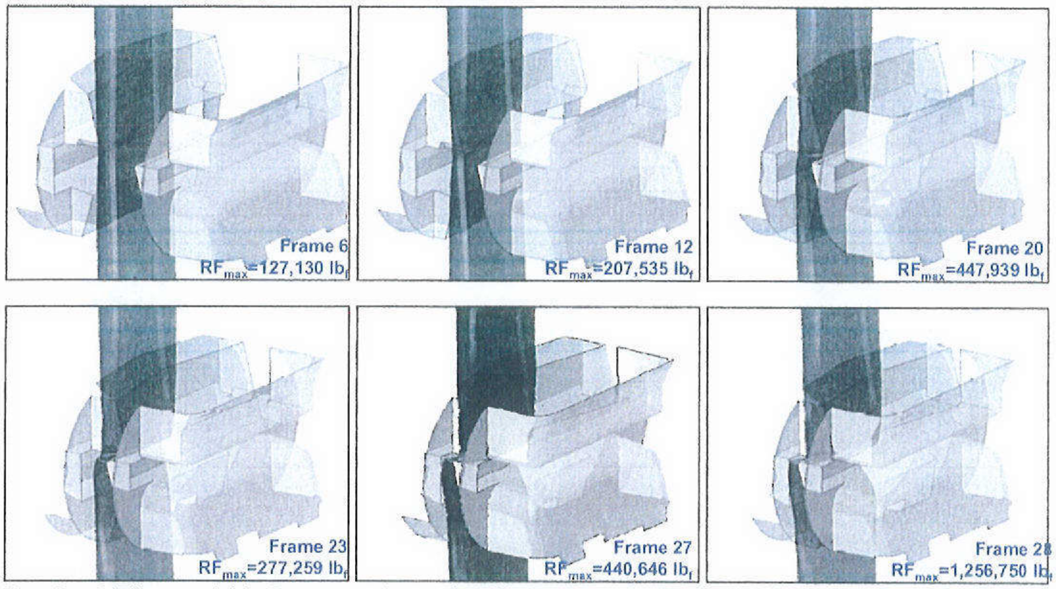
The progression of the shear cut for the model with off-centered drill pipe is shown in Revised Figure 139 and Revised Figure 140. With the pipe off center in the wellbore (displaced 0.5 inches from the inside wall of the wellbore as illustrated in Figure 134), the corner of the upper blade made the initial contact with the drill pipe (Frame 6). In Frame 12, the corner of the upper BSR blade has pierced the drill pipe and shearing has initiated. Because part of the pipe is outside of the upper BSR blade surface, only approximately 75% of the pipe is actually being sheared between the upper BSR and lower BSR blade surfaces (Revised Figure 141, Frame 23). Due to the shear initiation at the Kill Side end point of the upper BSR blade and the fact that less of the pipe was sheared between the upper and lower BSR blade surfaces, the calculated maximum shearing force / equivalent operating ram pressure was less than that calculated for the centered pipe model (1,882 psi equivalent pressure for the off-center pipe versus 2,408 psi equivalent pressure for the centered pipe).

The remainder of the pipe was deformed and sheared/torn outside of the upper BSR blade surface (Revised Figure 139 and Revised Figure 140, Frames 23, 27, and 28). There is tight clearance between the top blade face of upper BSR block and the opposite relief cavity on the lower BSR block, which provides a high resistance to closing the BSR blocks. The FEA model predicts that the tight clearance of these vertical surfaces initiates shearing in a vertical direction causing the corner of the pipe to be torn away. This would explain the physical evidence shown in Figure 58a (left side of photograph). The FEA model predicts a similar process occurs between the bottom face of the upper BSR block and the opposite relief cavity on the lower BSR block with the exception that the clearance between these surfaces is greater.

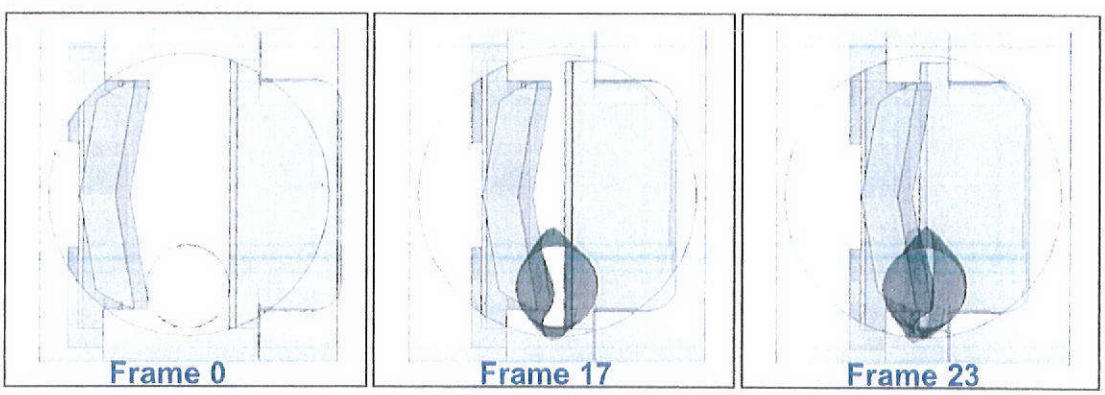
The point at which the sheared pipe is being deformed between the upper and lower BSR block faces (Revised Figure 139 and Revised Figure 140, Frames 27 and 28), the force to produce additional displacement increases very rapidly.



Revised Figure 139 Progression of Off-Center BSR Shear Model - Side View



Revised Figure 140 Progression of Off-Center BSR Shear Model - Isometric View

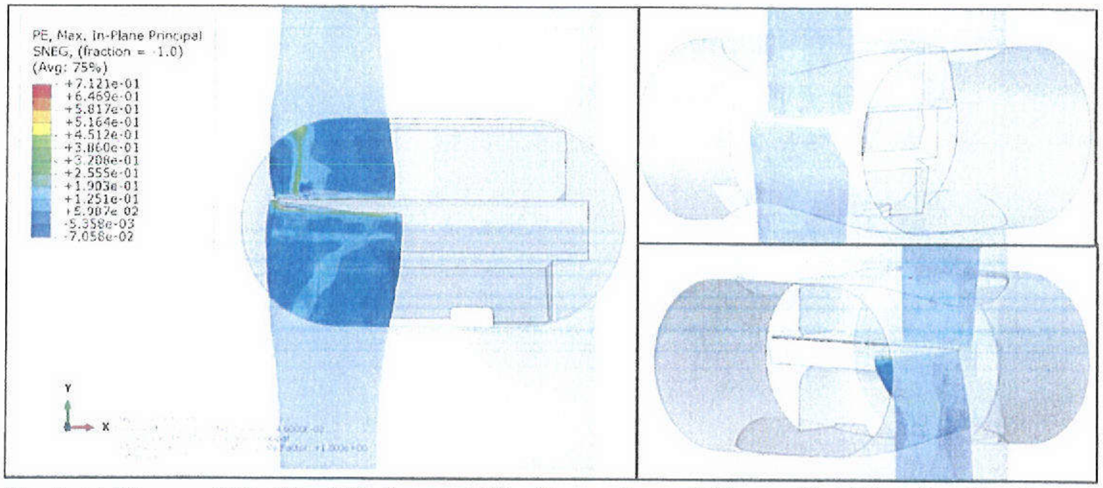


Revised Figure 141 Top View Showing Deformation of Drill Pipe Outside of Shearing Blade Surfaces

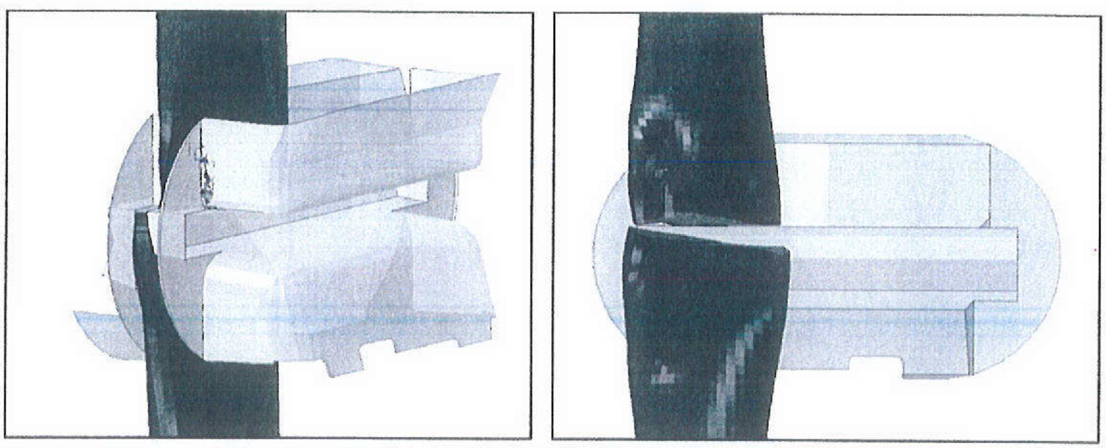
The configuration of the drill pipe for the condition shown in Frame 28 of Revised Figure 139 and Revised Figure 140 is referred to as the "final deformed" condition since it represents an operating ram pressure of 5,280 psi (greater than the available hydraulic pressure and thereby conservative for a maximum ram block displacement). Revised Figure 142 shows that, although the drill pipe was initially off-set 0.5 inch from the inside wall of the wellbore, the deformed pipe touches the wellbore surface both above and below the BSR cavity (Revised Figure 142). This is also the case for the lower operating ram pressures for Frames 23 and 27 (Revised Figure 139, Revised Figure 140, and Revised Figure 141; equivalent operating ram pressures of 1,165 and 1,851 psi, respectively)

Comparison between the segments of drill pipe and upper BSR block and the final configuration predicted by the FEA model showed good agreement when the block indentations on the recovered drill pipe segments were matched to the top and bottom upper BSR block faces (Revised Figure 144 and Revised Figure 145). The following observations are noted:

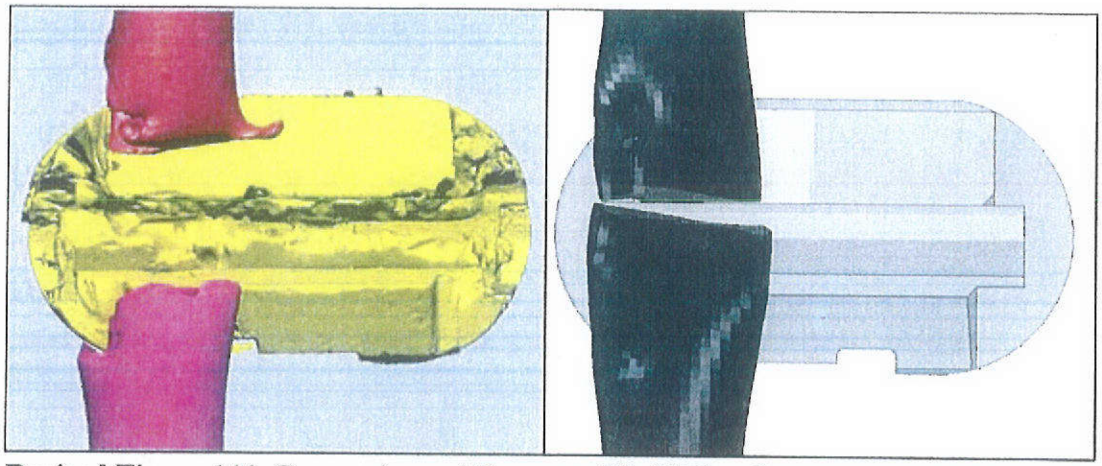
- For the FEA model, the ram block indentations on both the upper and lower segments of drill pipe were present and agreed with the recovered evidence (Revised Figure 143 and Revised Figure 145).
- If the "curled in" portion of upper segment of drill pipe was straightened, the recovered drill pipe would extend down to the cutting blade surface of the upper BSR block (Revised Figure 144).
- The notched (corners) missing on both the upper and lower segments of drill pipe correspond to the end of the top and bottom faces of the upper BSR block (Revised Figure 144).
- The vertical "cuts" of the notches (Figure 61 and Revised Figure 145) of the top and bottom drill pipe sections correspond respectively to (1) the tight tolerance between the BSR upper ram block top face and the opposite relief cavity of the lower ram block (sharp vertical cut of the notch on the top drill pipe – 83-B) and (2) the larger gap between the BSR upper ram block bottom face and the opposite relief cavity of the lower ram block (more deformation and tearing of the vertical cut of the notch on the bottom drill pipe – 94-B).
- If the fold-over on the lower drill pipe segment was sheared (center image in Revised Figure 145), the FEA model matches the recovered lower drill pipe segment of the BSR cut.



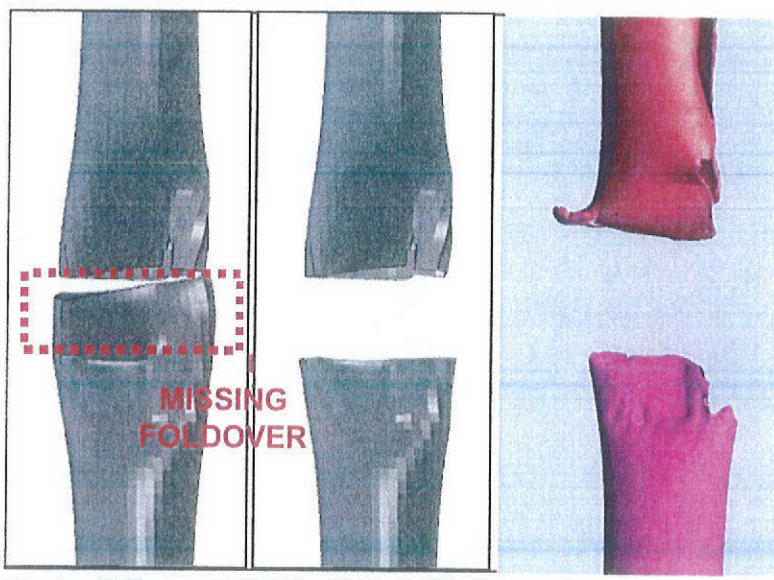
Revised Figure 142 Final Deformed Configuration of Shear Cut Showing Strain Concentration at Inner Bend



Revised Figure 143 Final Deformation of the Drill Pipe as Predicted by the Off-Centered Pipe Model; Upper BSR Block Shown on the Right



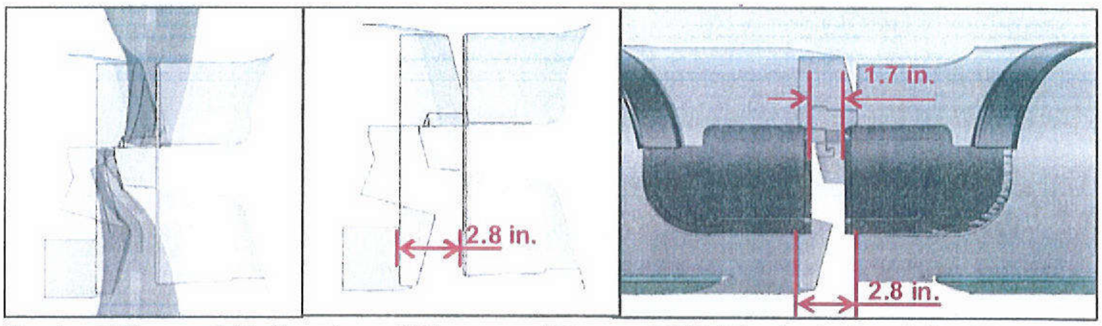
Revised Figure 144 Comparison of Recovered Drill Pipe Segments and Final Model (Viewed facing the Upper BSR Block)



Revised Figure 145 Final Model Deformation Compared with Recovered Drill Pipe Laser Scans - 83-B and 94-B

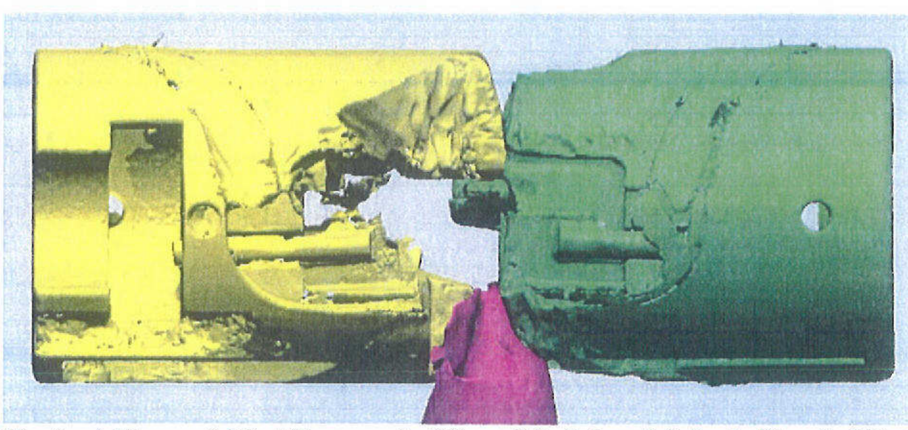
The FEA model predicted a 2.8-inch block displacement between the upper and lower BSR blocks for an applied force (RF_{MAX}) of 1,256,750 lb_f (equivalent to 5,280 psi). (See last frame in revised Figures 139 and 140.) The BSR would likely stall prior to the application of 5,280 psi, as the required pressure exceeds the available hydraulic system pressure (regulated to 4,000 psig), but the value of 5,280 psi was the model output closest to and not less than 4,000 psi. For comparison, the force in the prior frame is 440,646 lb_f which is equivalent to 1,851 psi. At this point, the force is rapidly increasing with little additional displacement of the BSR blocks due to the drill pipe deformation outside of the cutting surface of the BSR blades.

With an applied equivalent pressure of 5,280 psi (which is greater than the available hydraulic pressure), the upper and lower BSR blocks were 2.8 inches from being fully closed (Revised Figure 146 and Revised Figure 148). The side packers were 1.7 inches from making initial contact and sealing. The lower BSR blade was 2.2 inches from contacting the rear packers and sealing.

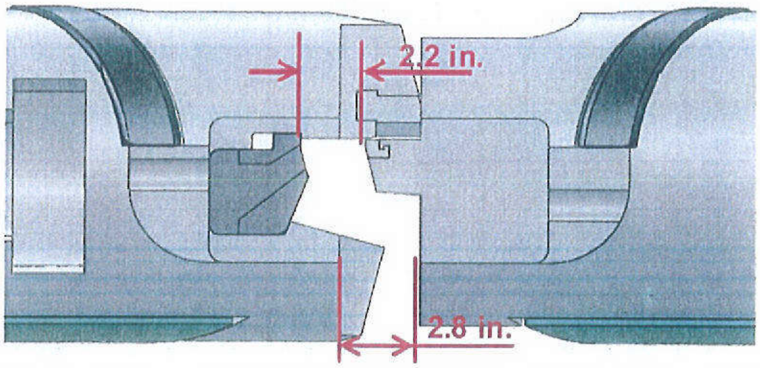


Revised Figure 146 Spacing of Upper and Lower BSR Blocks in Partially Closed Position

Further investigation was performed using the laser scanned models. The models of the upper and lower BSR blocks, and drill pipe segment 94 were assembled with segment 94 contacting the upper block (deformation features aligned – Revised Figure 147). With the blocks spaced 2.8 inches from fully closed and the lower block fit against segment 94 a large gap exists partly created by the BSR blocks not fully closing and partly due to erosion of the side packers, rear blade seal packers, and the ram blocks (especially on the Kill Side of the blocks).



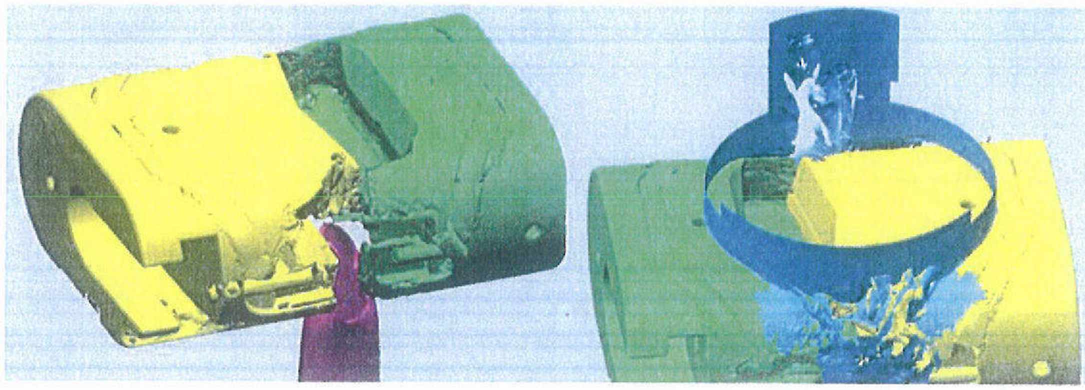
Revised Figure 147 Alignment of Scan Models – 2.8 Inch Standoff between Blocks



Revised Figure 148 BSR CAD Models – 2.8 Inch Standoff between Blocks

With the VBRs closed below the BSR, well flow was diverted through the inside of the drill pipe. After the BSR was activated and closed on the off-center drill pipe, the well flow was concentrated through the partially sheared drill pipe on the kill side of the BSR. The kill side of the blocks and wellbore experienced the most erosion damage. This concentrated flow condition remained until the CSRs were activated (April 29, 2010) shearing the drill pipe. This created a new flow condition that was no longer concentrated on the kill side of the BSR. Flow then exited the cut drill pipe below the CSR and impinged upon the bottom of the CSR blocks (evidenced by erosion pattern on recovered blocks). The CSR was intended only to cut tubulars. It was not designed to seal the wellbore. Without a sealing mechanism in the CSRs, flow traveled around the CSR blocks and continued up the entire wellbore cross-section below the BSRs. Without contact between the lower blade and rear packer (forming a seal), flow occurred across the entire face of the BSR blocks. This flow condition existed from April 29, 2010, until the well was brought under control.

Revised Figure 149 shows the open cavity through the upper BSR block above the cut lower drill pipe segment. The image on the right shows the scan of the erosion in the wellbore along the kill side of the BSRs.



Note the image on the left is viewed from the kill side, while the image on the right is facing the kill side of the wellbore.

Revised Figure 149 Erosion Damage - BSR Blocks and Wellbore

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