Appendix V. BP Deepwater Horizon GOM Incident Investigation Dispersion Analysis (from BakerRisk)

BP DEEPWATER HORIZON GOM INCIDENT INVESTIGATION

DISPERSION ANALYSIS

Final Report
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Prepared for:
bp

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Notice

EXECUTIVE SUMMARY

Baker Engineering and Risk Consultants, Inc. (BakerRisk) has performed a flammable gas dispersion evaluation for the Deepwater Horizon offshore drilling rig based on information provided by BP. The FLACS (FLame ACceleration Simulator) computational fluid dynamics (CFD) model was employed to perform the dispersion evaluation. BakerRisk built a simplified geometry within the FLACS pre-processor using available photographs and layout drawings provided by BP as guidance. This simplified solid model geometry duplicated the large-scale features of the Deepwater Horizon (e.g., buildings, hull openings, etc.). Ventilation air supply and exhaust fans were also included within the FLACS model. The background wind field was modeled with a constant velocity of 2 m/s blowing port to starboard based on data provided by BP. Over the course of the investigation, BP postulated two likely release scenarios. The first, Scenario A, represents an upper limit release rate based upon initial well inflow modeling and the second, Scenario B, represents a lower limit refinement based upon alternative well inflow interpretations.

<u>Scenario A:</u>
The initial simulated release scenario, provided by BP, was a prolonged, 8.5 minute event involving time-dependent, sequential release of gas from each of the five release locations shown in Table ES-1. The flammable gas release rate as a function of time for each location is shown in Figure ES-1. Note that the total release rate is plotted on the right hand axis.

Table ES-1. Release Location Descriptions (Scenario A)

Release Point	Location	Description
1	Riser bore at drill floor (unobstructed)	Vertical release through the riser annulus at drill floor level without impingement on surfaces above release (release flows through openings in rotary table).
2	Mud Gas Separator (MGS) vent at top of rig	Release through a vent directed downward (vent is goose necked).
3	MGS Rupture Disk / Diverter Outlet (starboard)	Horizontal release directed outward (from near edge of vessel) at the diverter starboard overboard line.
4	Slip joint below moon pool	Release from riser annular space on packer joint.
5	Mud processing system (tanks and mud pit room exhaust vent)	Release from open-top tanks and subsequent horizontal release from mud room exhaust vent directed aft.

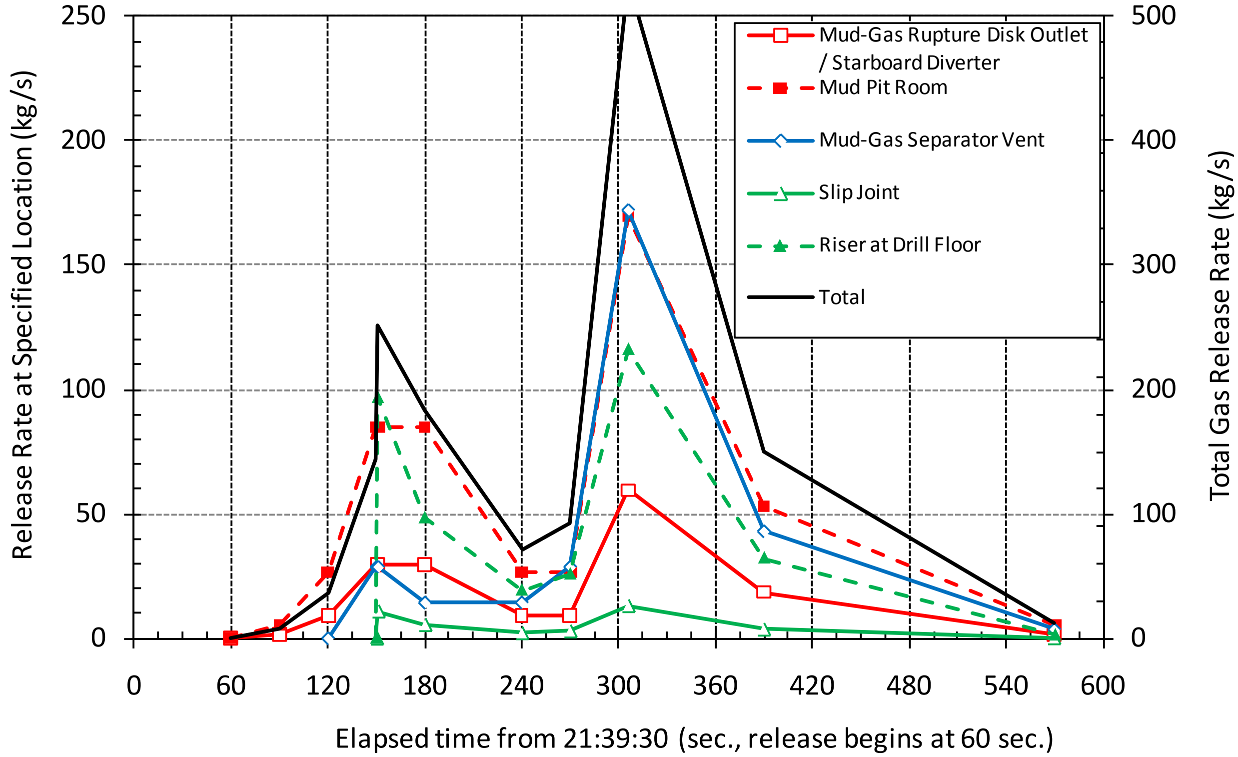


Figure ES-1. Gas Flow Rate as a Function of Time for each Release Location (Scenario A)

The flammable vapor cloud developed due to the Scenario A release is shown at 300 seconds after the initiation of the release (i.e. at 360 seconds) in Figure ES-2. This figure provides 3D flammable concentration contours viewed looking aft from port-forward and forward from aft-starboard. The outer surface of these contours represents the lower flammability limit of the gas mixture (1.5%). This figure indicates that at five minutes (300 seconds) after the start of the Scenario A release, a flammable vapor cloud has developed that extends over all but the port edge of the main deck.

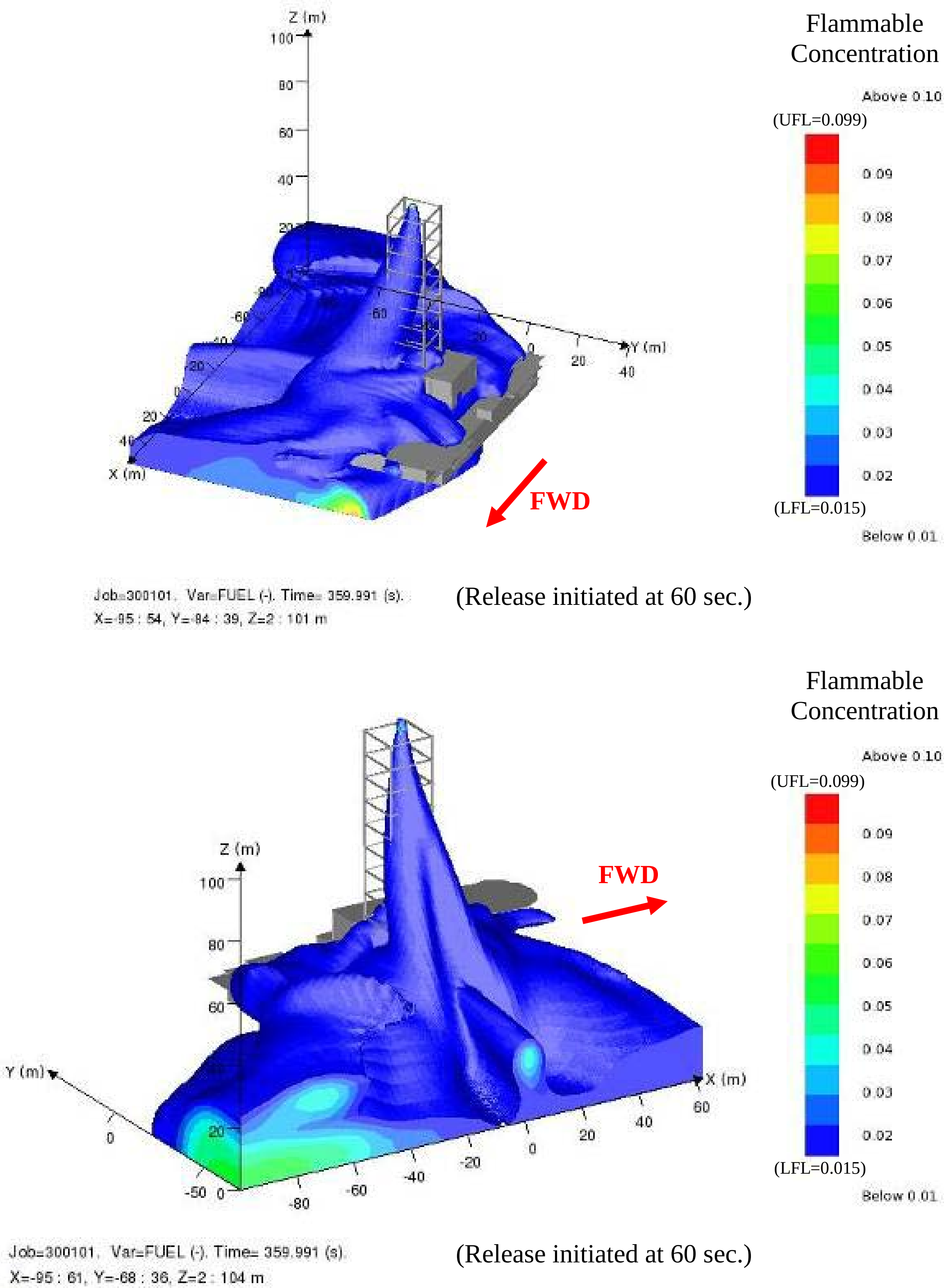


Figure ES-2. Flammable Cloud at 360 seconds (3D, Scenario A)

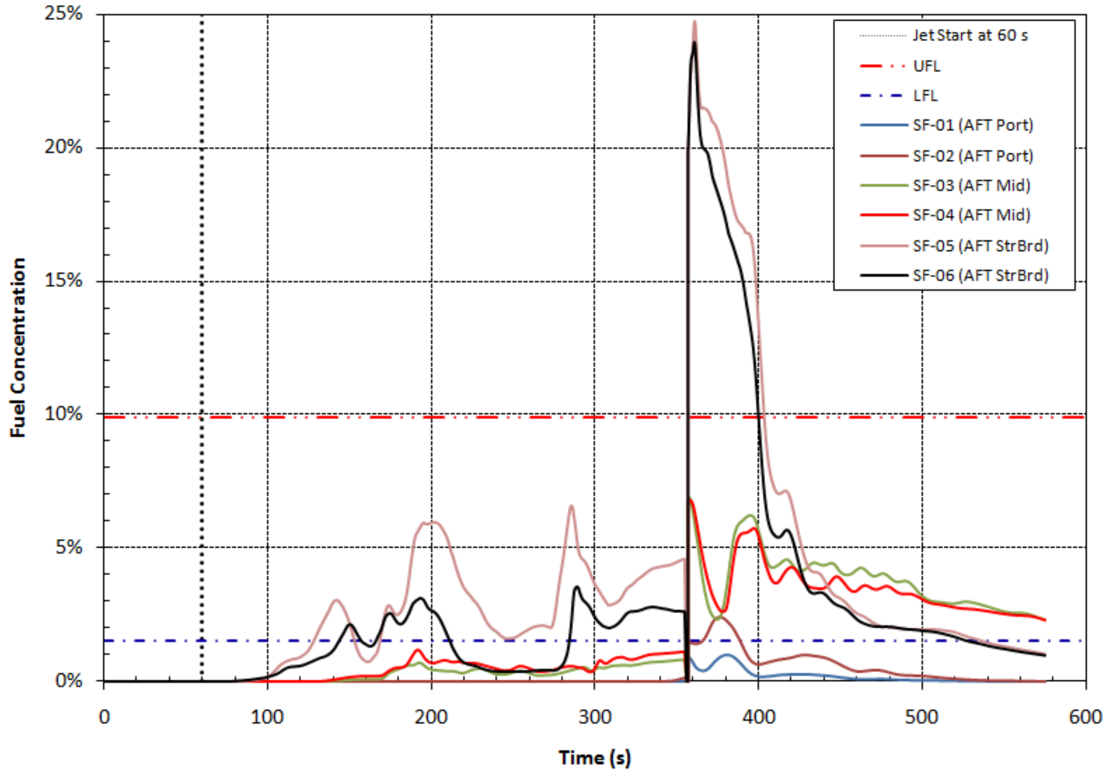


Figure ES-3. Engine Room Ventilation Intake Flammable Gas Concentration History (Scenario A)

Figure ES-3 shows the fuel concentration as a function of time at the engine room ventilation air intake locations on the aft end of the main deck. The fuel gas concentration at the engine room #5 and #6 supply air intakes (SF-05 and SF-06, respectively) enters the flammable range between 60 and 90 seconds after the start of the release. At 300 seconds after the start of the release, the gas concentration at these locations peaks at over 20%, well above the upper flammability limit of the gas mixture (9.9%). This corresponds to roughly one minute after the gas flow rate through all five release points has peaked. After about 50 more seconds, the gas concentration at SF-05 and SF-06 re-enters the flammable range. At this time, the concentration at the ventilation air intakes for engine rooms #3 through #6 (SF-03, SF-04, SF-05, and SF-06) are within the flammable range and remain so for over two minutes.

These results demonstrate that this release scenario is capable of developing flammable gas concentrations at the engine room #3 through #6 ventilation air intakes. It is feasible that given this release scenario, a flammable gas mixture could have formed within these four engine rooms.

Scenario B:

The second simulated release scenario provided by BP was intended to focus on the initial potential dispersion of a partially restricted (e.g. BOP attempting to close, riser / drill pipe potentially blocked with debris, etc.) well flow rate. In effect, Scenario B is intended to more closely represent a lower boundary case as compared to Scenario A. Additional information regarding equipment design limits, relief points, and set points were also incorporated. For computer modeling efficiency and consistency with the analysis focus, this scenario was limited in duration to six minutes. In the actual event, gas flow continued beyond six minutes. The Scenario B release points are shown in Table ES-2. The flammable gas release rate as a function of time for each location is shown in Figure ES-4. It is noted that the total release rate for Scenario B is roughly 20% of that for Scenario A.

Table ES-2. Release Location Descriptions (Scenario B)

Release Point	Location	Description
1	Riser bore at drill floor (unobstructed)	NOT USED IN THIS SCENARIO
2	Mud Gas Separator (MGS) vent at top of rig	Release through a vent directed downward (vent is goose necked)
3	MGS Rupture Disk outlet (starboard)	Horizontal release directed outward (from near edge of vessel) alongside the diverter starboard overboard line
4	Slip joint below moon pool	Release from annular space on packer joint
5	Mud processing system (tanks and mud pit room exhaust vent)	Release from open-top tanks and subsequent horizontal release from mud room exhaust vent directed aft
6	MGS Vacuum Breaker vent	Located approximately 1/3rd of the way up the derrick. Directed downward (vent is gooseneck)

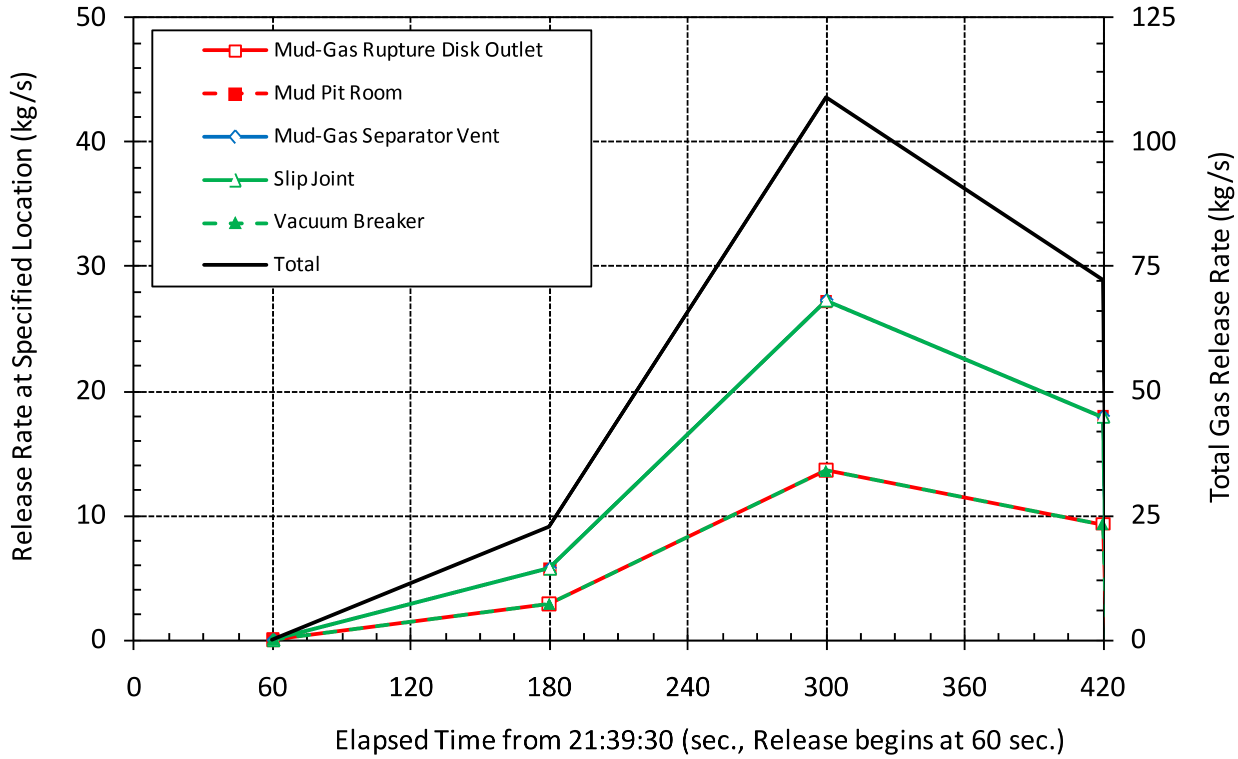


Figure ES-4. Gas Flow Rate as a Function of Time for each Release Location (Scenario B)

The flammable vapor cloud developed due to the Scenario B release is shown at 180 seconds after the initiation of the release (i.e. at 240 seconds) in Figure ES-5. This figure provides 3D flammable concentration contours viewed looking aft from port-forward and forward from aft-starboard. The outer surface of these contours represents the lower flammability limit of the gas mixture (1.5%). This figure indicates that at three minutes (180 seconds) after the start of the Scenario B release, a flammable vapor cloud has developed that extends around the air bottle rack forward of the derrick and that engulfs the starboard-aft quadrant of the main deck. Note that the extent of the flammable gas cloud approaches the starboard edge of the catwalk at the center of the aft side of the main deck.

Figure ES-6 shows the fuel concentration as a function of time at the engine room ventilation air intake locations on the aft end of the main deck. The fuel gas concentration at the engine room #5 supply air intake (SF-05) enters the flammable range approximately 170 seconds after the start of the release and remains flammable for over 140 seconds. The fuel gas concentration at the engine room #6 supply air intake (SF-06) reaches the lower flammable limit (1.5%) approximately 250 seconds after the start of the release and falls back below the lower flammable limit less than 10 seconds thereafter.

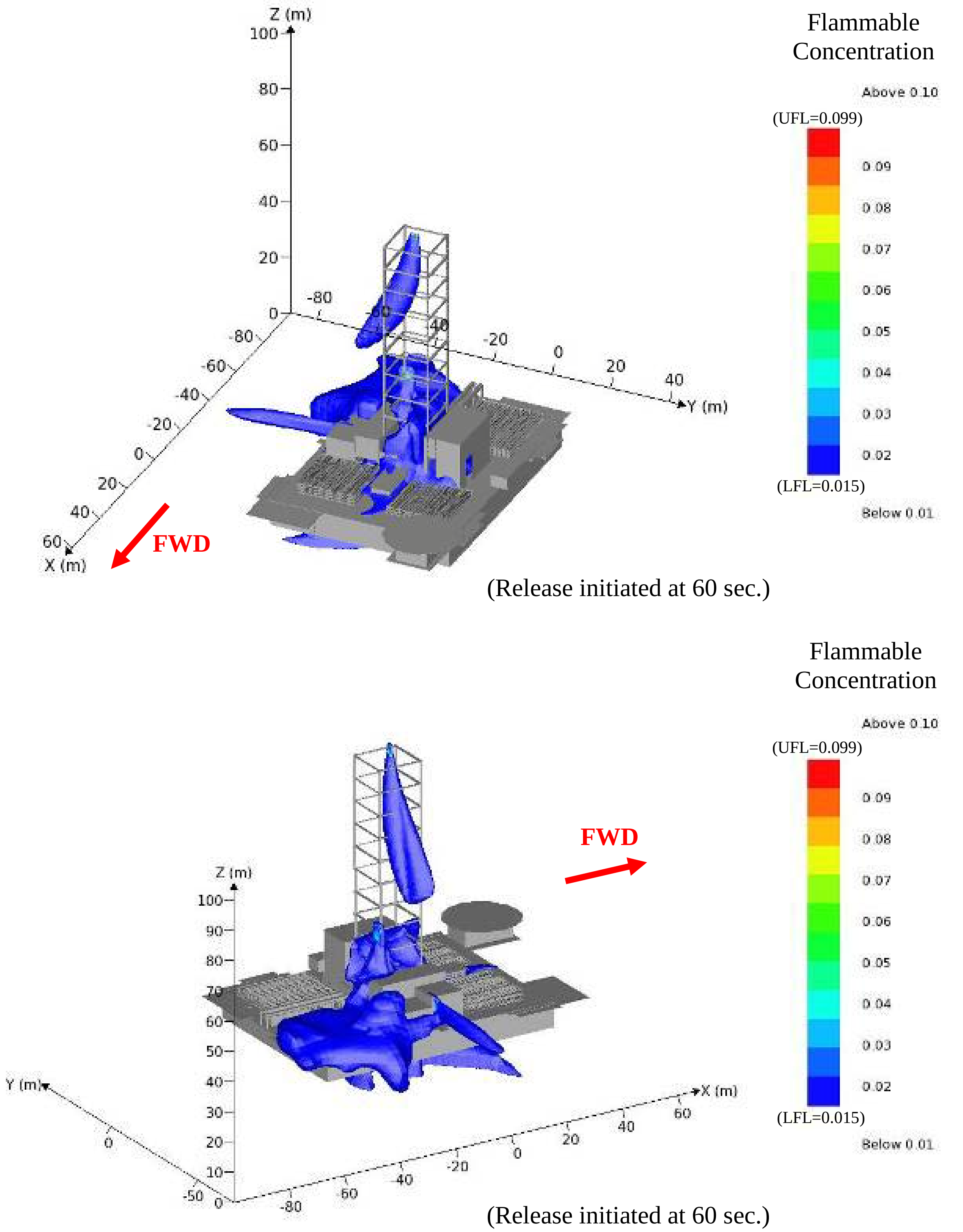


Figure ES-5. Flammable Cloud at 240 seconds (3D, Scenario B)

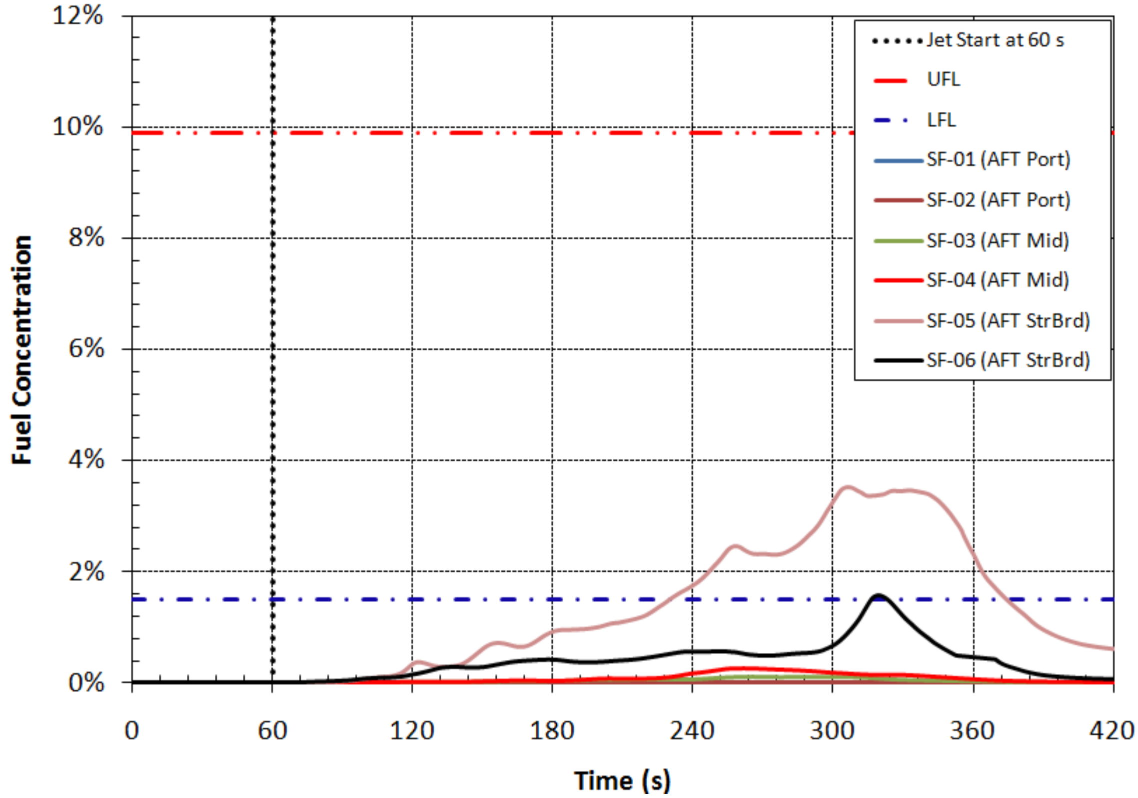


Figure ES-6. Engine Room Ventilation Intake Flammable Gas Concentration History (Scenario B)

At the lower limit release rates assumed for Scenario B, the flammable gas concentrations are not predicted to exceed the lower flammability limit at the engine room #3 or #4 supply air intakes (SF-03 and SF-04, respectively). However, it should be noted that variations in wind direction and wind speed were not considered in this evaluation and the actual arrangement of non-permanent objects on the main deck is not known and was therefore not reflected in the solid model. It is expected that such factors could perturb the flow field and flammable gas dispersion behavior around the location of the supply air intakes sufficiently that the flammable gas concentration at SF-03 and SF-04 could exceed the lower flammability limit.

These results demonstrate that the Scenario B release is capable of developing a flammable gas mixture at the engine room #5 and #6 ventilation air intakes. It is also possible that the flammable gas concentration at the engine room #3 and #4 ventilation air intakes could have exceeded that lower flammability limit.

Table of Contents

Appendices

List of Tables

List of Figures

1 INTRODUCTION

Baker Engineering and Risk Consultants, Inc. (BakerRisk) has performed a flammable gas dispersion evaluation for the Deepwater Horizon offshore drilling rig based on information provided by BP. The purpose of this report is to present the results of this evaluation.

BakerRisk employed the commercially available FLACS (FLame ACceleration Simulator) computational fluid dynamics (CFD) model to perform the dispersion evaluation. FLACS was originally developed by GexCon AS of Norway, primarily for simulating dispersion of gas leaks and subsequent explosions in congested and confined offshore oil and gas production platforms. The latest version of FLACS has many more applications, such as explosion mitigation measures (grating, vent panel and opening, water spray, etc.) as well as safety and risk studies in the land-based process industry. A description of FLACS is provided in Appendix A. FLACS version 9.1 was used in this work.

Section 2 presents an outline of the methodology followed to employ FLACS in the dispersion evaluation. A description of the Deepwater Horizon is given in Section 3, followed by a discussion of the release parameters in Section 4. Section 5 describes the FLACS solid model geometry. Section 6 contains a discussion of the results of the dispersion evaluation.

2 METHODOLOGY

FLACS requires as input a 3D solid model of the structures and equipment around and through which simulations are to be performed. These are normally provided in the form of 3D CAD models. Since 3D CAD models were not available, BakerRisk built a simplified geometry within the FLACS pre-processor using available photographs and layout drawings provided by BP as guidance. This simplified solid model geometry duplicated the large-scale features of the Deepwater Horizon (e.g., buildings, hull openings, etc.). A description of the Deepwater Horizon based on the available photographs and drawings is provided in Section 3 and a description of the FLACS solid model geometry is provided in Section 5.

Gas dispersion is modeled in FLACS by specifying a release point, or points, an orientation for each release point, the composition of the fuel being released, a release rate (which can be variable at each release point), and a release duration. The subsequent migration of gas throughout and around the solid model geometry is dictated by both the momentum of the gas released at each point and by the background air flow provided by the ambient wind conditions and/or forced ventilation systems. A detailed description of the release locations, fuel composition, wind conditions, ventilation system, and release sequence utilized in the study is provided in Section 4.

3 SHIP DESCRIPTION

An overview photograph of the Deepwater Horizon drill ship hull is given as Figure 1.

Figure 1. Overview Photograph (showing aft end and starboard side)

The upper hull is 74 meters (243 ft) long (i.e., fore to aft) and 61 meters (200 feet) wide (i.e., starboard to port). The upper hull section is 8.5 meters (27.9 ft) deep. The main deck is comprised of the topside hull and the drill floor positioned at the center of the ship. The BOP house is located on the port side of the derrick and the draw works, mud room, and drill store are located on the starboard side of the derrick. Aft of the derrick on the main deck there is riser storage and a catwalk. Forward of the derrick on the main deck there are pipe racks and a large air bottle rack. There are two decks, the second and third decks, contained within the hull; the third deck at the bottom of the hull is also referred to as the lower deck. The heights of the second and third decks are both approximately 3.5 meters (11.5 ft). The moon pool is an open volume located at the center of the ship extending from beneath the drill floor through the lower deck.

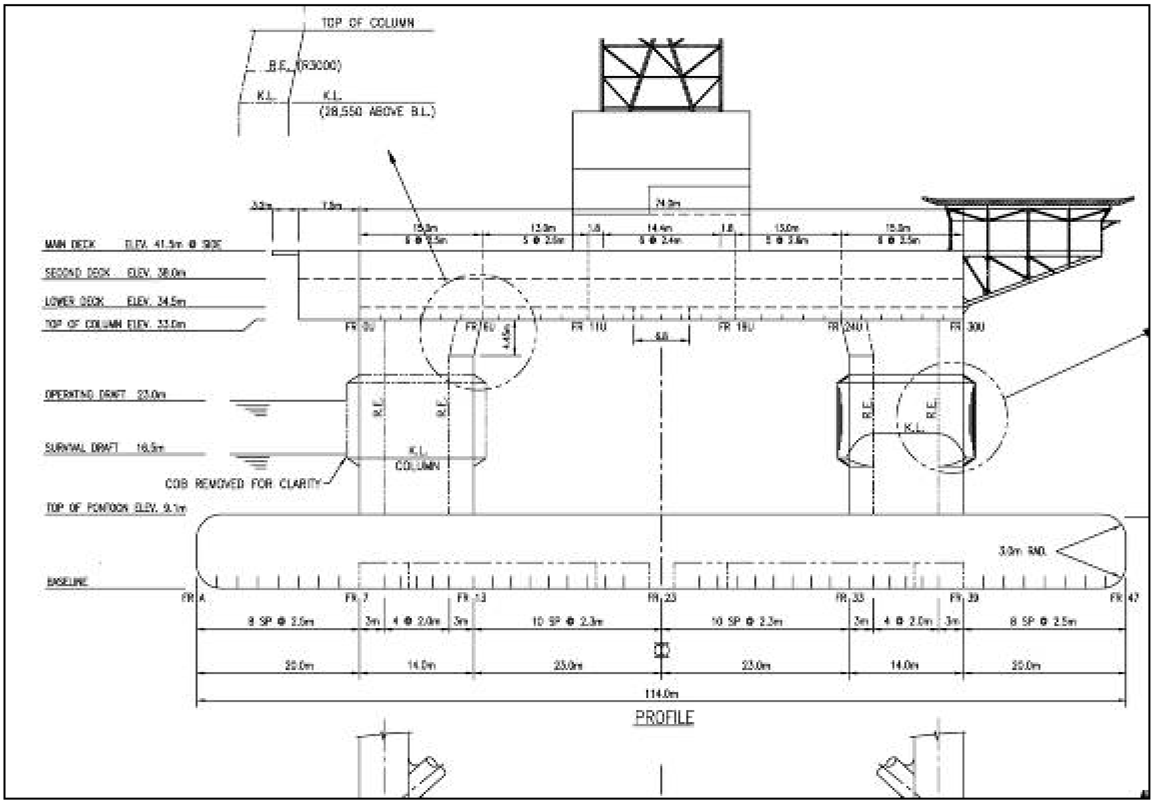
A simplified line drawing of the ship is given as Figure 2. Layout (plan view) drawings of the ship showing the upper hull, main deck, second deck and third deck are given as Figure 3 through Figure 6. Elevation view drawings from the port and starboard sides are given as Figure

7 and Figure 8, respectively, and elevation views from the front (bow) and rear (stern) are given as Figure 9 and Figure 10, respectively. Photographs of the aft catwalk are given as Figure 11 through Figure 13. Photographs of the forward bottle rack are given as Figure 14 and Figure 15.

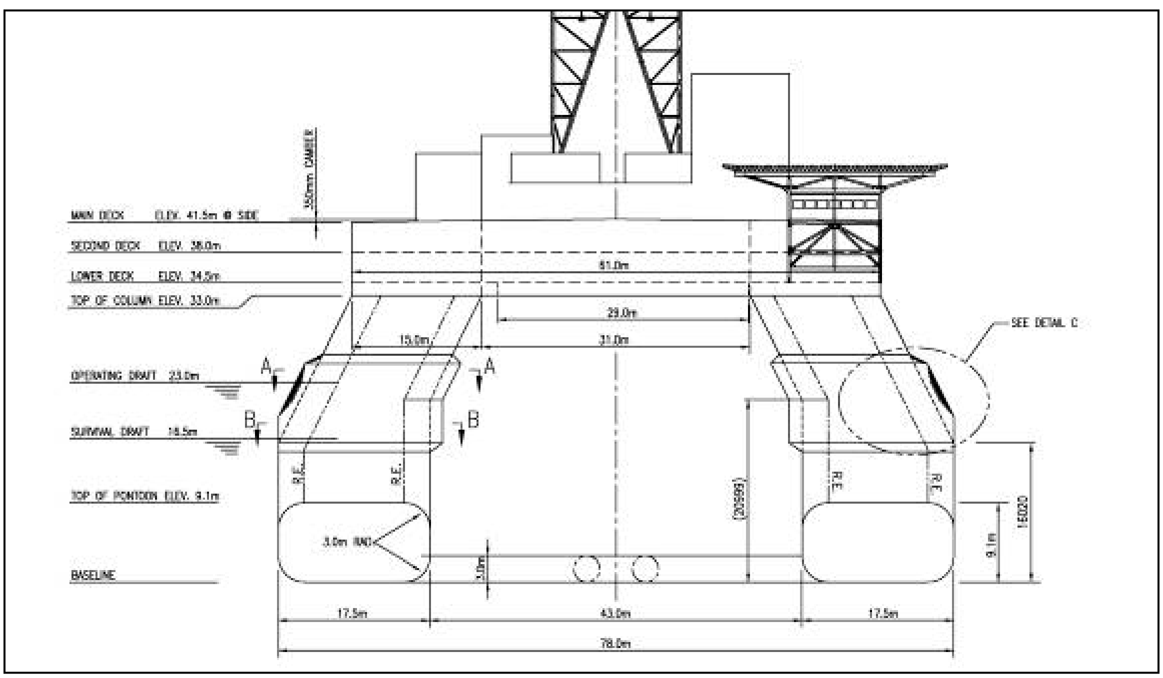
There are two large doors providing access to the BOP house, one is on the forward side of the port wall and the other is on the port side of the forward wall. These doors are shown Figure 7 and Figure 9, respectively. Photographs of these doors are given in Figure 16 through Figure 18. There are no external openings on the aft portion of the port wall or on the starboard or aft walls of the BOP house, as seen in Figure 19.

The forward wall between the main deck and the drill floor contains three openings to the moon pool, as indicated in Figure 9. These openings are also shown in Figure 20 and Figure 21. There are no openings to the outside on the starboard or aft sides of the moon pool, as shown in Figure 22 and Figure 23.

Additional details on the ship are presented in the discussion of the release scenarios as required to explain and illustrate the scenarios.



(view from side)



(view from bow)

Figure 2. Simplified Line Drawing (HRBS-058-000-P0612-1, rev.5)

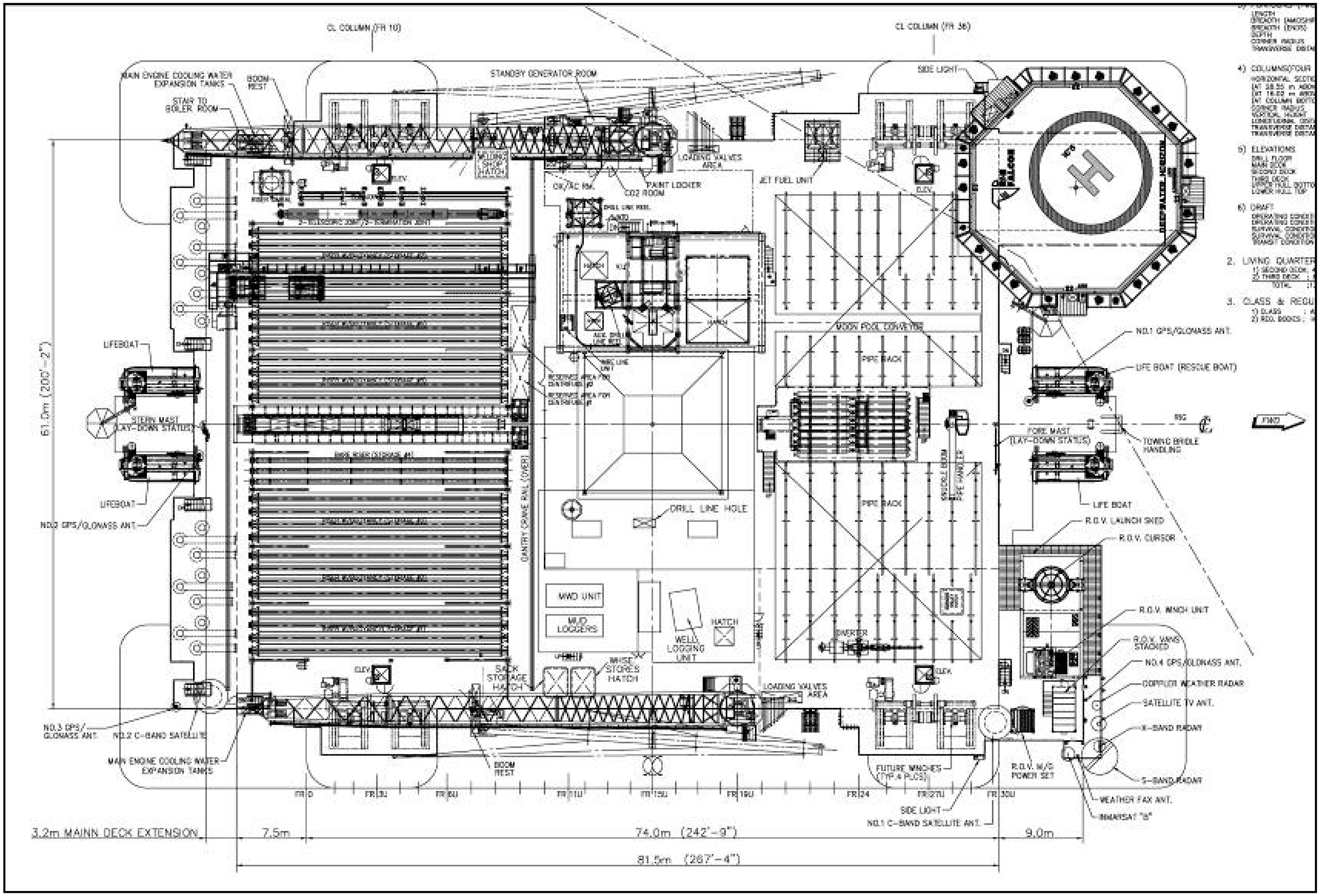


Figure 3. Upper Hull Layout Drawing (HRBS-058-000-P0601, rev.5)

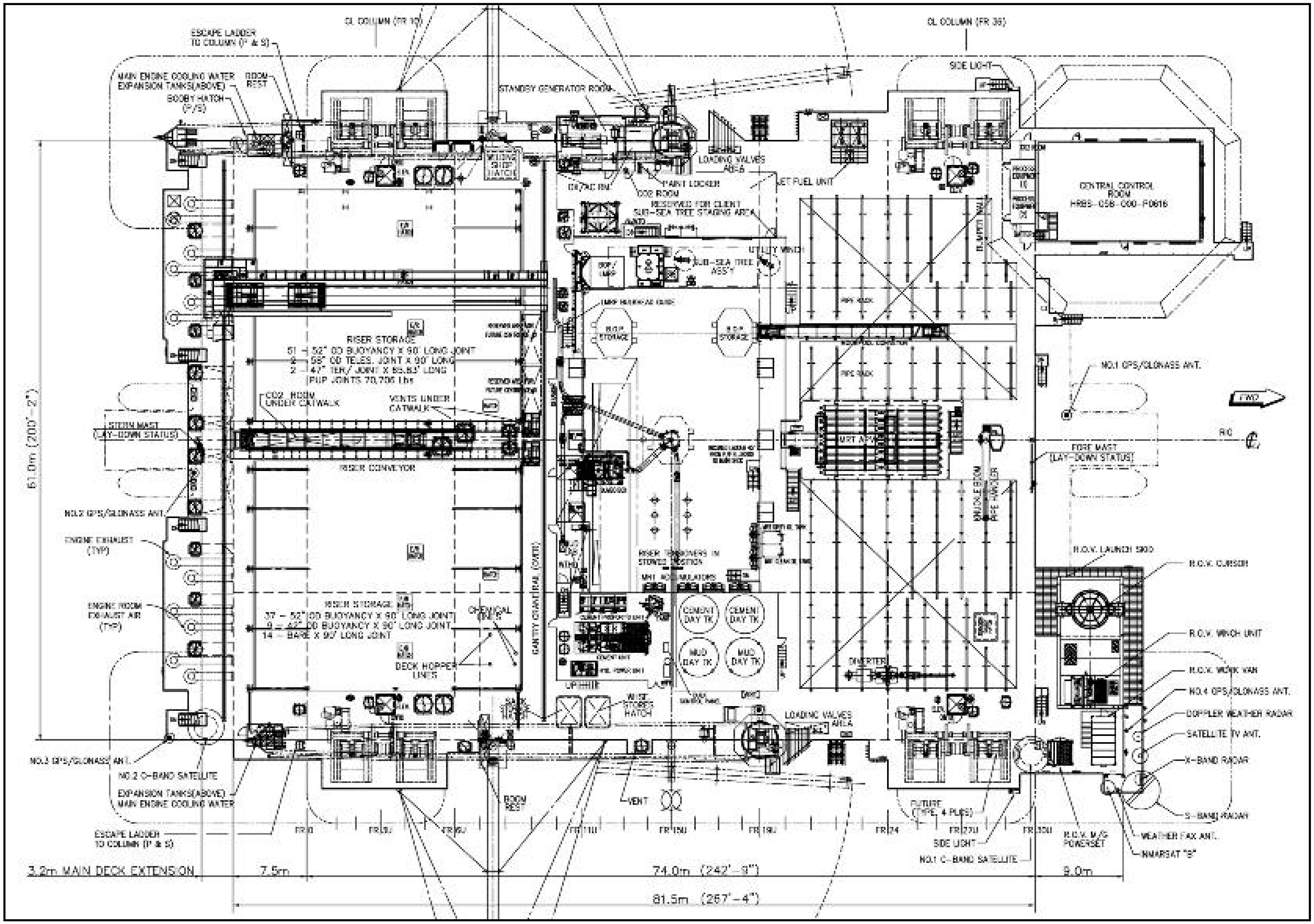


Figure 4. Main Deck Layout Drawing (HRBS-058-000-P0607, rev.5)

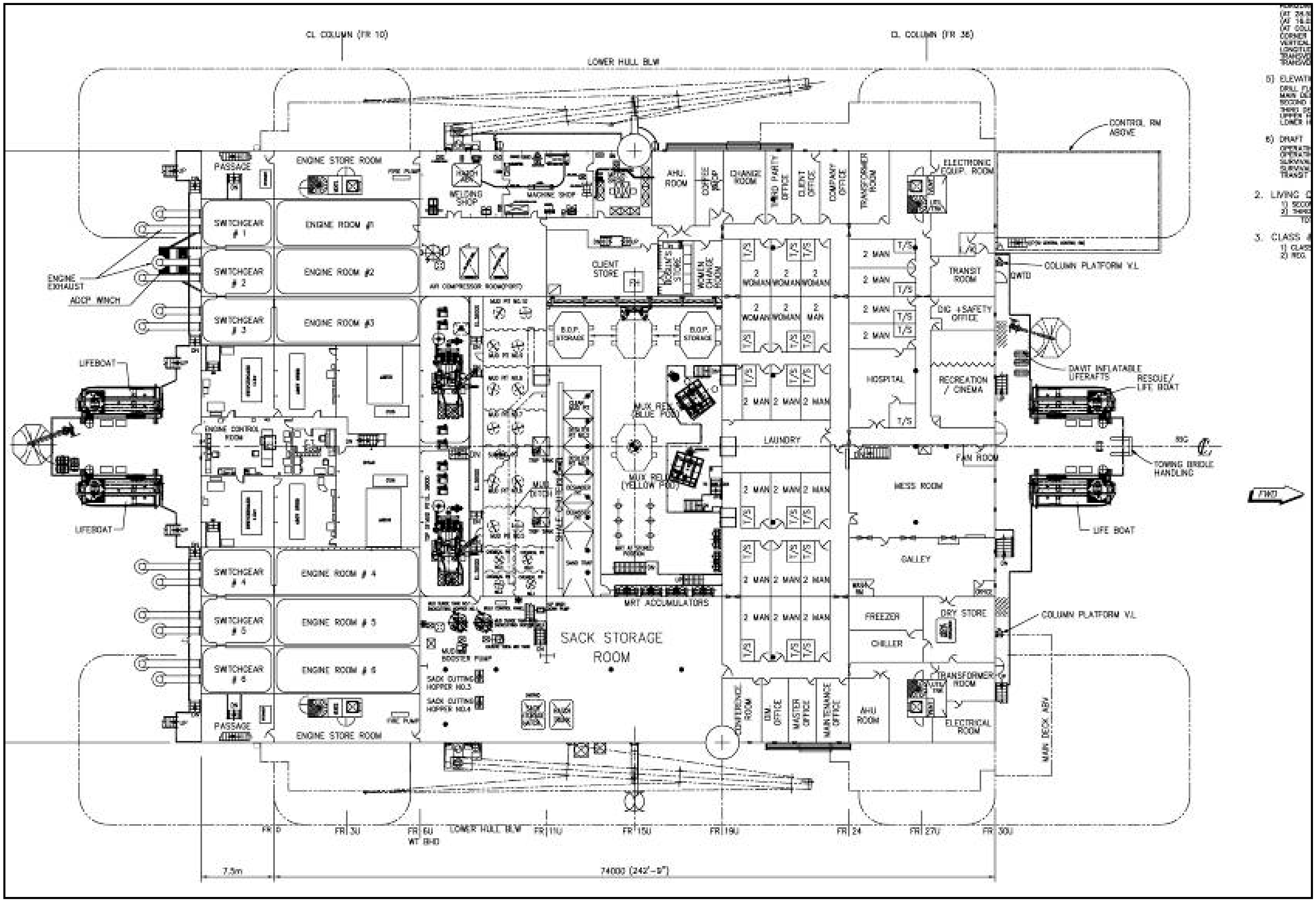


Figure 5. Second Deck Layout Drawing (HRBS-058-000-P0608, rev.5)

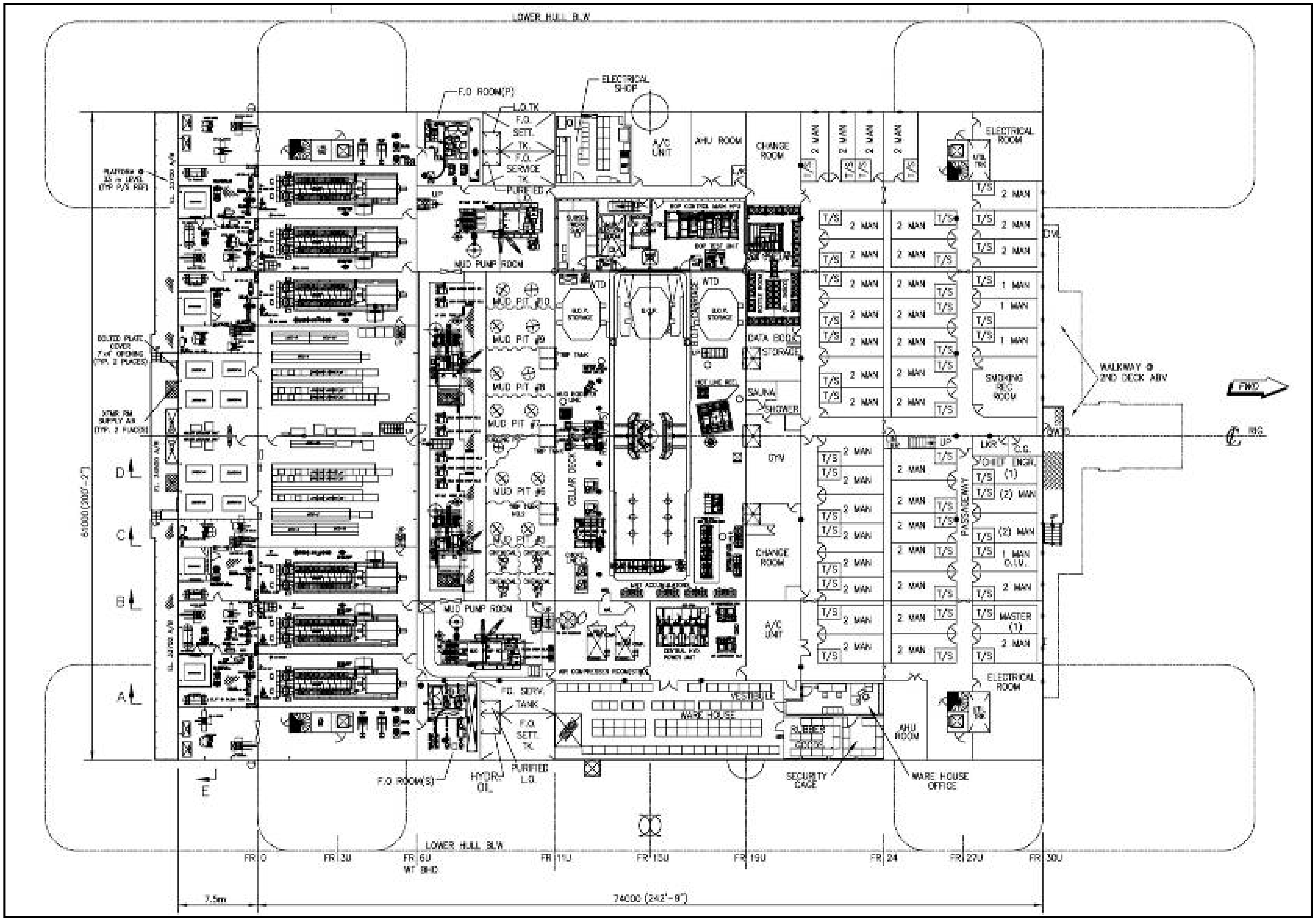


Figure 6. Third Deck Layout Drawing (HRBS-058-000-P0609, rev.5)

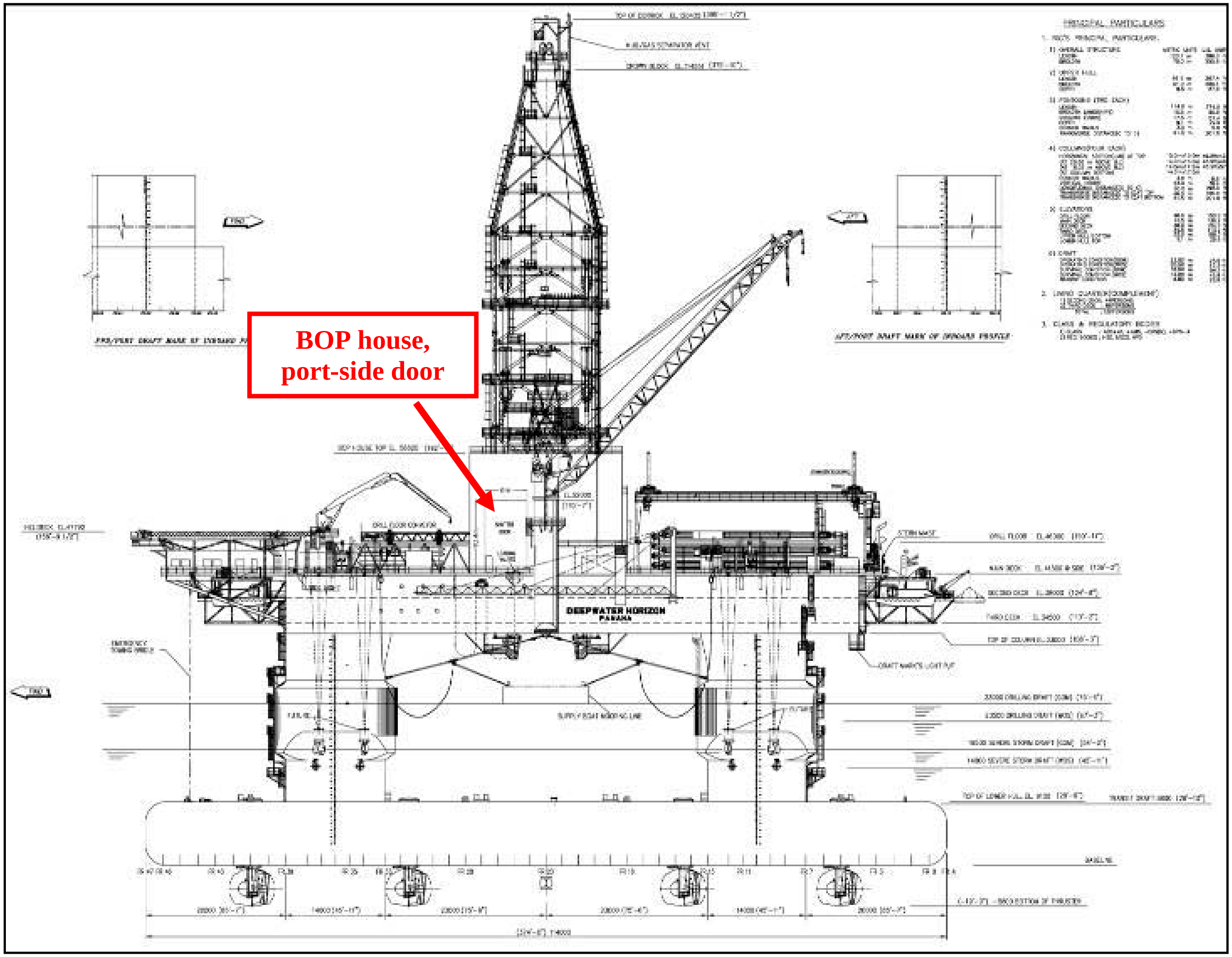


Figure 7. Elevation View from Port Side (HRBS-058-000-P0602, rev.5)

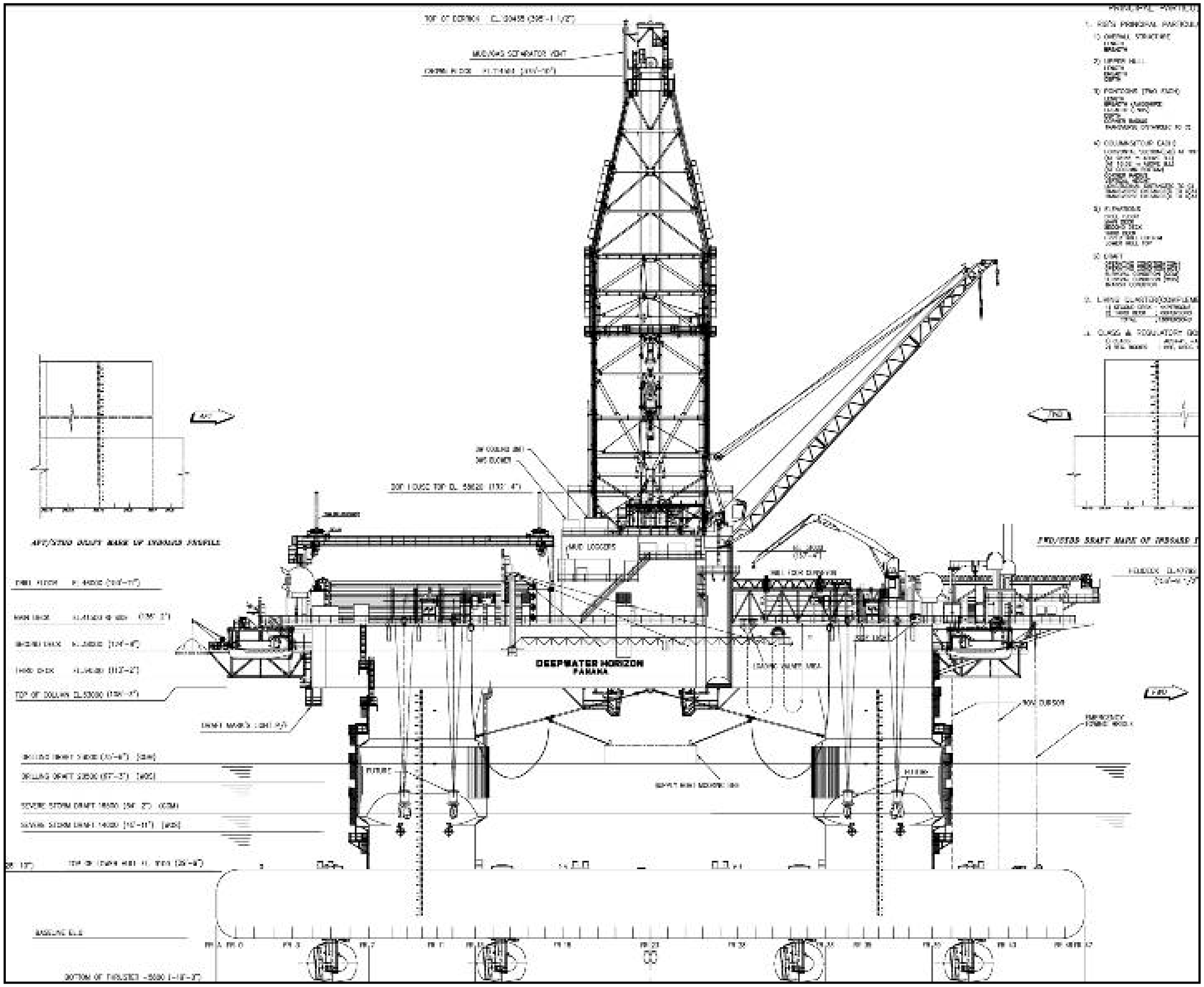


Figure 8. Elevation View from Starboard Side (HRBS-058-000-P0603, rev.5)

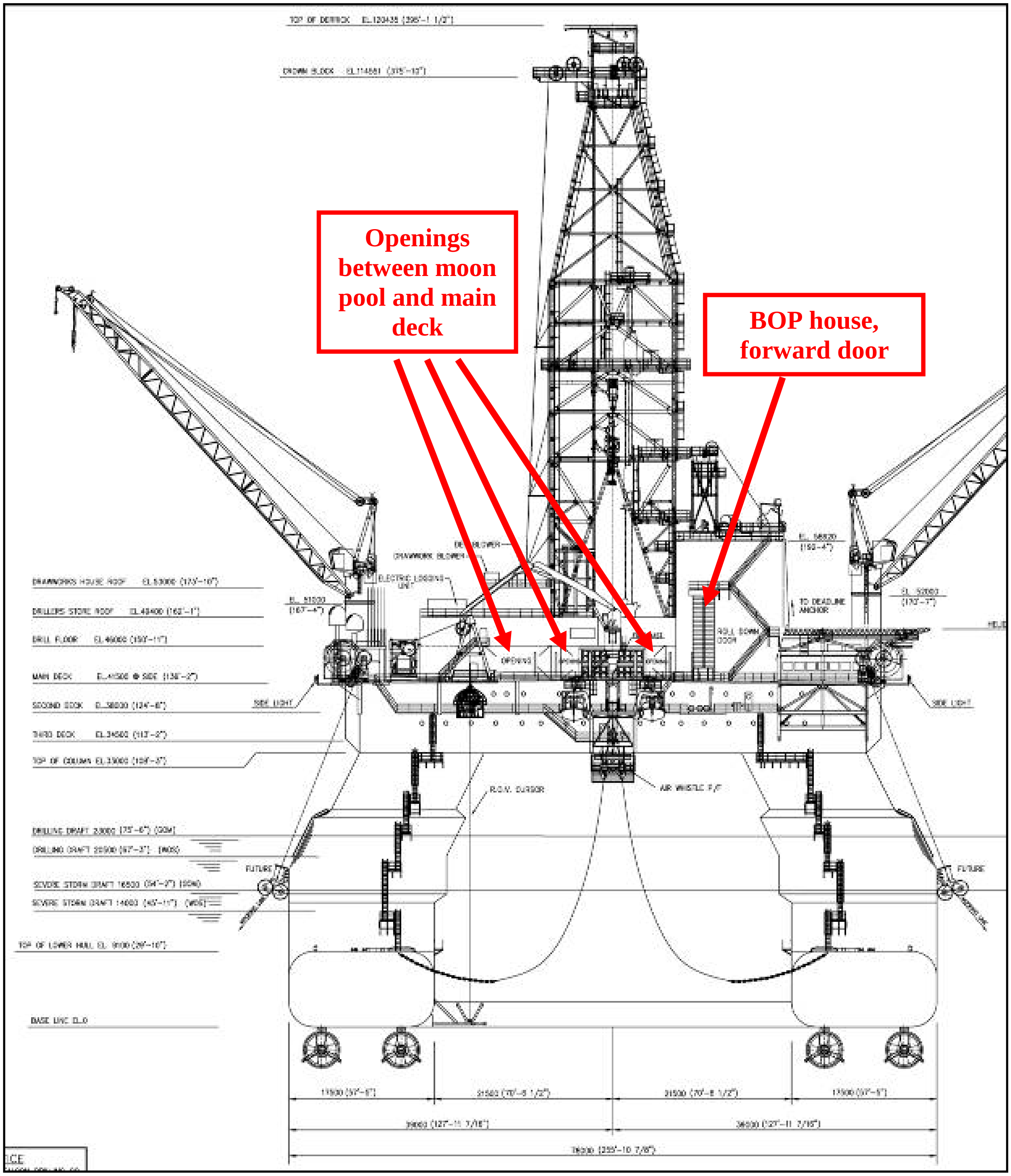


Figure 9. Elevation View from Bow (HRBS-058-000-P0604, rev.5)

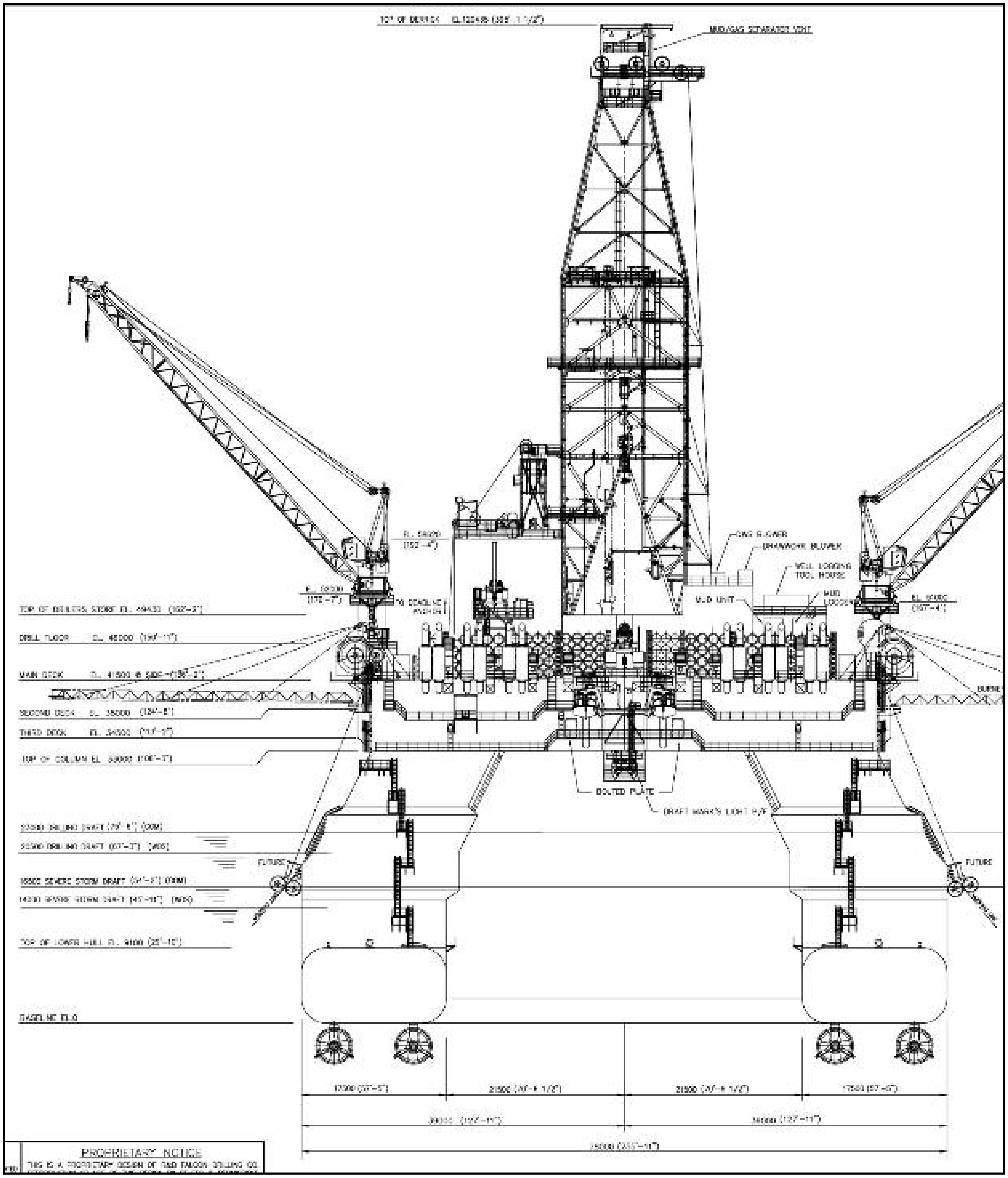


Figure 10. Elevation View from Stern (HRBS-058-000-P0605, rev.5)

Figure 11. Aft Catwalk Viewed from Port Looking Aft Starboard

Figure 12. Aft Catwalk Viewed from Aft Port Looking Forward

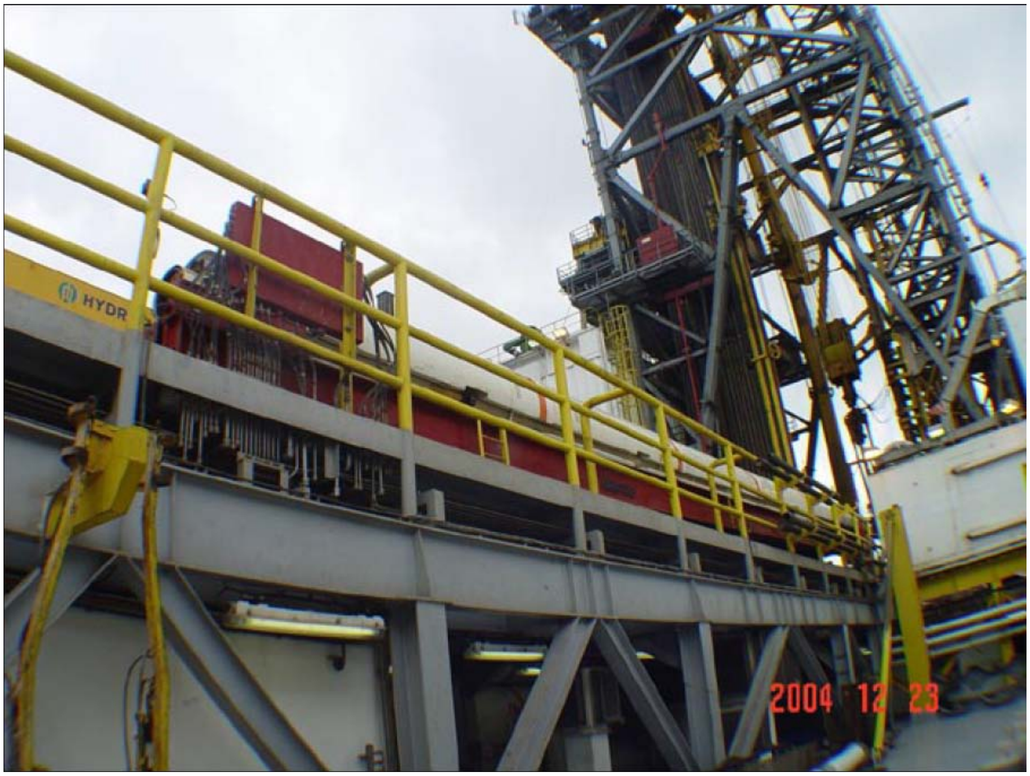


Figure 13. Aft Catwalk Viewed from Starboard Looking Forward Port

Figure 14. Forward Bottle Rack Viewed from Port Looking Starboard

Figure 15. Forward Bottle Rack Viewed from Forward End

Figure 16. Doors in the BOP House Viewed from Forward Port

Figure 17. Door at Forward Side of BOP House Viewed from Inside Looking Forward

Figure 18. Forward Port Wall of BOP House Viewed from Inside Looking Forward Port

Figure 19. Starboard and Aft Walls of BOP House Viewed from Inside Looking Aft

Figure 20. Forward Profile of Ship

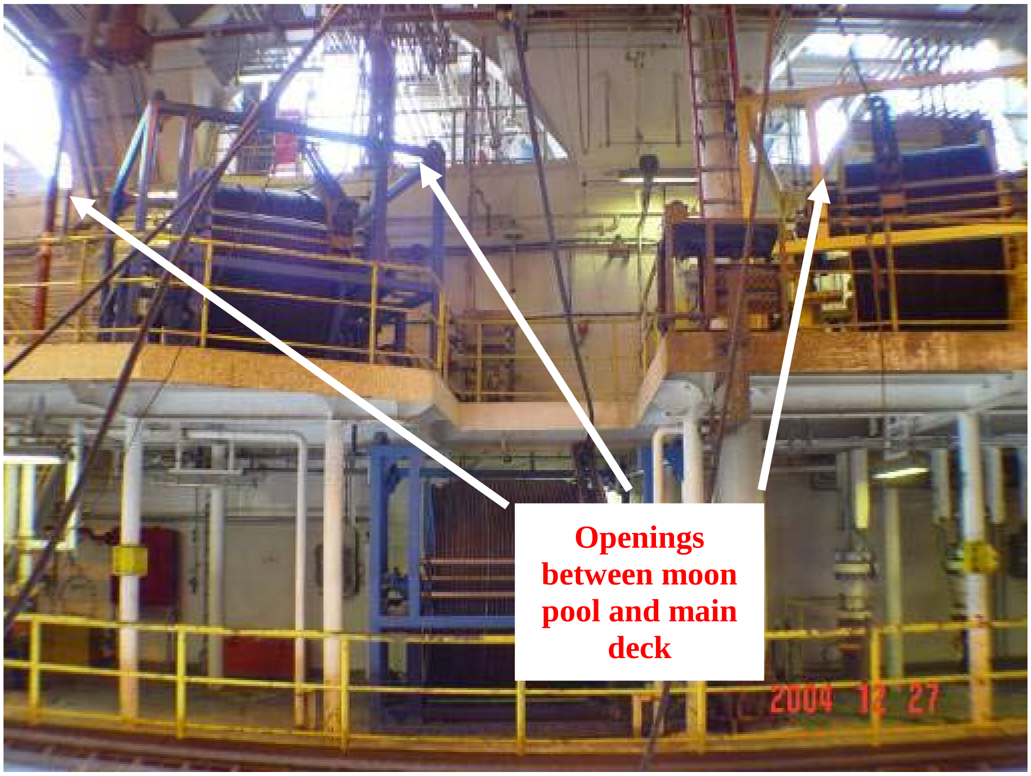


Figure 21. Forward Wall of the Moon Pool Viewed from Inside Looking Forward

Figure 22. Looking Starboard across Moon Pool (Aft Wall is to the Right)

Figure 23. Profile of Ship Viewed from Starboard Aft

4 MODEL PARAMETERS

The release points considered in the dispersion evaluation are given in Table 1. Two release scenarios were modeled: Scenario A and Scenario B. Each release scenario was a prolonged event involving time-dependent, near simultaneous release of gas from multiple release locations. In Scenario A, release points one through five were considered, and in Scenario B, release points two through six were considered. A more detailed description of each release location and the associated input data and assumptions is given in the following sub-sections.

Table 1. Release Location Descriptions

Release Point	Location	Description
1	Riser bore at drill floor (unobstructed)	Vertical release at drill floor level without impingement on surfaces above release (release flows through openings in rotary table*). Scenario A only*.
2	Mud Gas Separator (MGS) vent at top of rig	Release through a vent directed downward (vent is goose necked).
3	MGS Rupture Disk outlet (starboard)	Horizontal release directed outward (from near edge of vessel) alongside the diverter starboard overboard line.
4	Slip joint below moon pool	Release from annular space on packer joint.
5	Mud processing system (tanks and mud pit room exhaust vent)	Release from open-top tanks and subsequent horizontal release from mud room exhaust vent directed aft.
6	MGS Vacuum Breaker vent	Located approximately one-third of the way up the derrick. Directed downward (vent is gooseneck). *Scenario B only*.

4.1 Fuel Composition

The estimated composition of the released gas is provided in Table 2. A simplified gas composition, given in Table 3, was utilized for the dispersion analysis in FLACS. The simplified composition was selected to capture the major species and maintain the mixture molecular weight. The Scenario A dispersion analysis was performed with release rates at individual release points ranging from 0 to over 150 kg/s with a maximum cumulative release rate exceeding 500 kg/s. The Scenario B dispersion analysis was performed with release rates at individual release points ranging from 0 to 27 kg/s with a cumulative release rate of approximately 110 kg/s.

4.2 Wind Conditions

The wind conditions at the time of the event are shown in Figure 24. The ship heading was 135° (i.e., the bow was pointing in this direction). The wind was blowing towards a direction between 220° and 250° (i.e., generally from port to starboard) at 1.5 m/s with gusts up to 2.6 m/s. All dispersion analyses discussed in this report were performed with a wind direction of port to starboard (i.e., 225°) and a wind speed of 2 m/s.

Table 2. Estimated Gas Composition (provided by BP)

Component	Concentration (%)
N2	0.624
CO2	0.974
C1	65.918
C2	6.374
C3	4.439
iC4	0.92
nC4	2.083
iC5	0.845
nC5	1.024
C6	1.341
C7	1.934
C8	2.092
C9	1.536
C10	1.285
C11-13	2.542
C14-19	2.904
C20-28	1.758
C29+	1.407

Table 3. Simplified Gas Composition for FLACS Analyses

Component	Symbol	Concentration (%)
Carbon Dioxide	CO_2	0.84
Methane	CH_4	57.18
Ethane	C_2H_6	5.53
Propane	C_3H_8	3.85
Butane	C_4H_{10}	2.60
Pentane	C_5H_{12}	1.62
Hexane	C_6H_{14}	1.16
Heptane	C_7H_{16}	1.68
n-Octane	C_8H_{18}	1.81
n-Nonane	C_9H_{20}	1.33
n-Decane+	$C_{10}H_{22}$	22.38

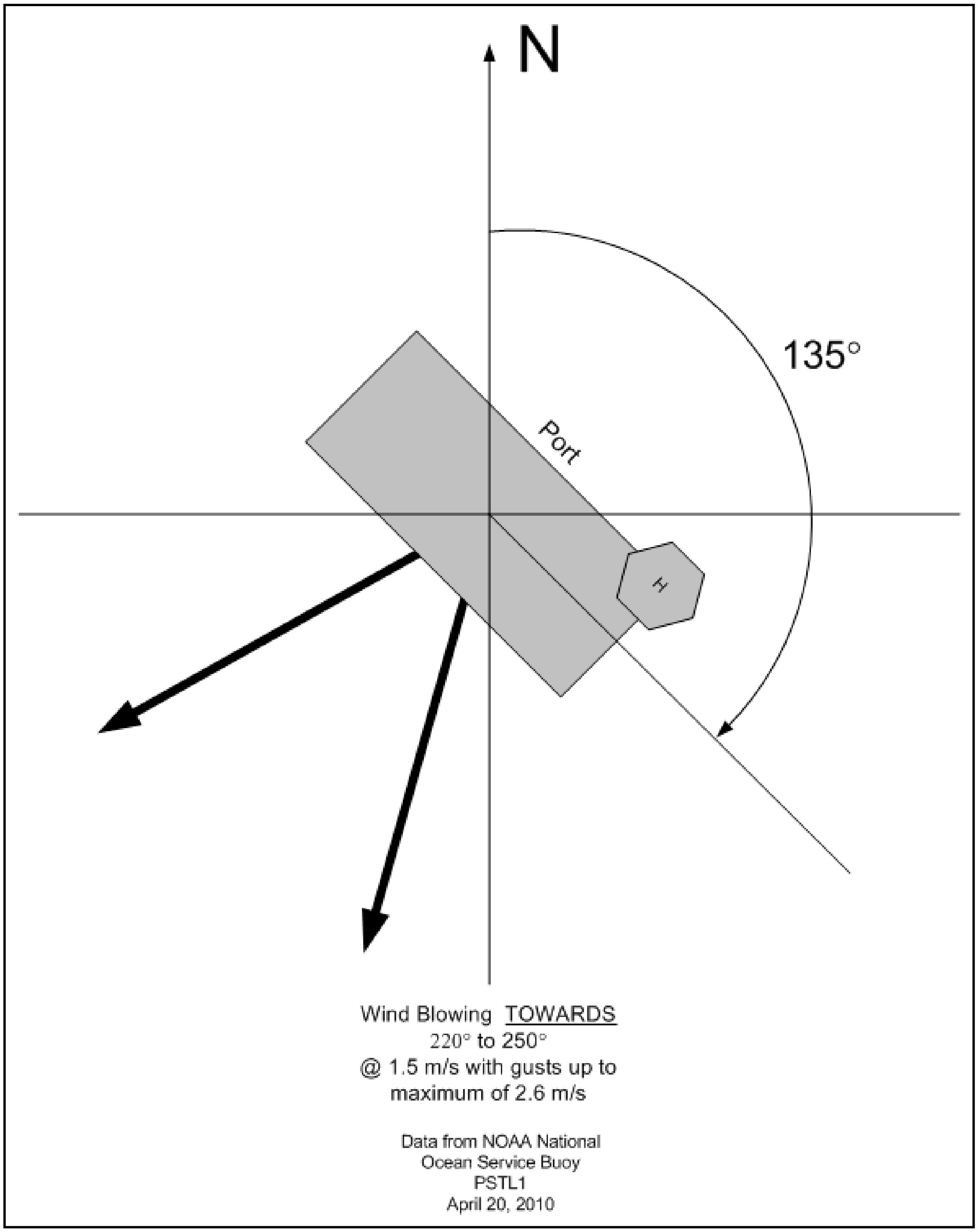


Figure 24. Wind Conditions

4.3 Ventilation System

The concentration of fuel at the ventilation inlets of the engine rooms, particularly in the case of the starboard and mid-ship engine rooms (i.e., engine rooms #5, #6, #3, and #4, respectively), is of interest for the overall release scenario. The engine rooms are located on the aft end of the ship and extend through the height of the hull (i.e., the engine rooms take up both the second and third decks); the engine room location is called out on the 2nd deck layout drawing, and can be seen on the 3rd deck layout drawing (i.e., Figure 5 and Figure 6, respectively). The 'A' and 'B' sections through an engine room shown in 3rd deck layout (Figure 6, lower left hand side) are shown below in Figure 25.

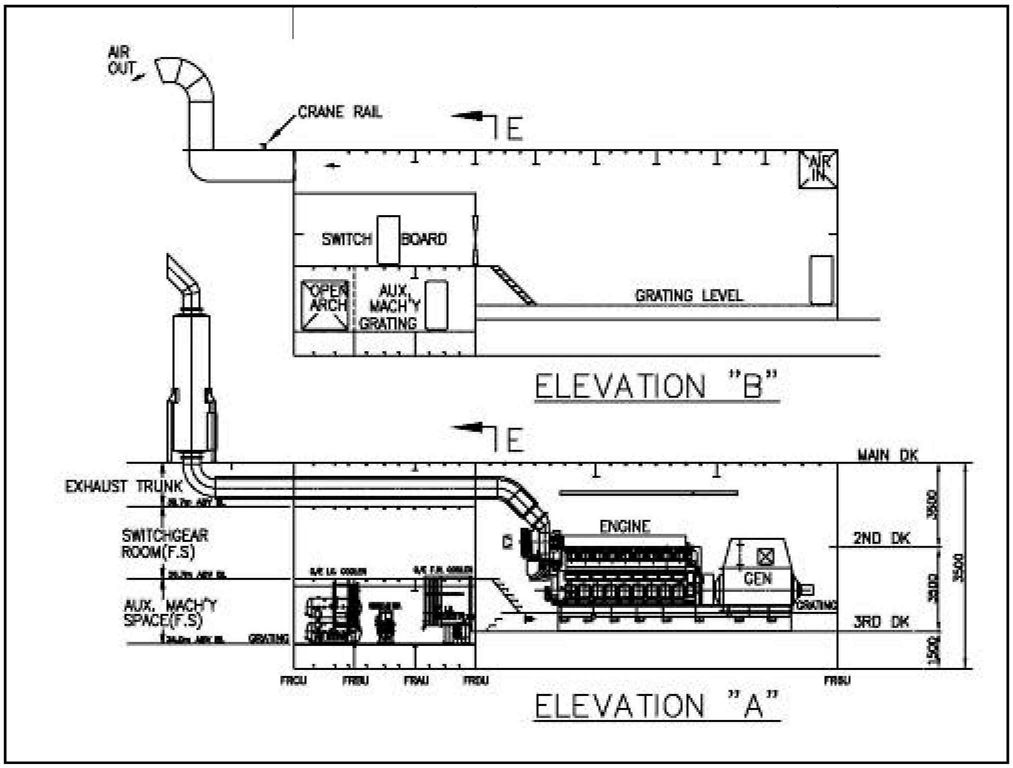


Figure 25. Engine Room Elevations (HRBS-058-000-P0609, rev.5)

The ventilation inlets for engine rooms #5 and #6 are on the starboard side of the aft end of the ship. The ventilation inlets for engine rooms #3 and #4 are aft of the derrick under the catwalk at mid-ship. These are shown on the main deck layout drawing (i.e., Figure 4). The aft starboard section of this layout drawing is shown as Figure 26 with the #5 and #6 engine room ventilation inlets called out. The mud room ventilation exhaust, which is relevant to release point 5 (see Table 1), is also called out in this figure. Supply fans SF-05 and SF-06 are associated with the ventilation inlets for engine rooms #5 and #6 (per drawing HRBS-H68-000-H1010, rev.2). The aft mid-ship section of this layout drawing is shown as Figure 27 with the #3 and #4 engine room ventilation inlets called out. Supply fans SF-03 and SF-04 are associated with the ventilation inlets for engine rooms #3 and #4 (per drawing HRBS-H68-000-H1010, rev.2).

These supply and exhaust fans are called out in Figure 28 and Figure 29, both of which are portions of the ship ventilation system drawings. Figure 30 shows the #3, #4, #5, and #6 engine room ventilation inlets and mud room ventilation exhaust locations on a main deck layout drawing, with Figure 31 showing an expanded view of the aft starboard portion of the deck. As shown in Figure 31, the #5 and #6 engine room ventilation intakes are mounted on the main deck with each intake fitted with three louvers, each 1.45 m by 2.1 m in area. The sides of the #5 and #6 engine room ventilation system intakes which face one another do not have louvers. The #3 and #4 engine room ventilation intakes are fitted with four louvers, each 1.7 m by 0.9 m in area. Figure 31 also shows that the mud room EF-15 and EF-16 ventilation exhausts are fitted with two louvers each, with each louver being 1.25 m by 1.0 m in area; the EF-17 mud room ventilation exhaust is fitted with a single 0.7 m by 1.0 m louver. The total ventilation exhaust flow area for the mud room is therefore 5.7 m^2 (61 ft^2). Figure 31 also indicates that the mud room ventilation exhaust louvers are all oriented aft (i.e., toward the rear of the ship). The capacities of the EF-15 and EF-16 fans are 14,825 scfm each, and that of the EF-17 fan is 5,000 scfm, giving a total mud room exhaust flow of 34,650 scfm.

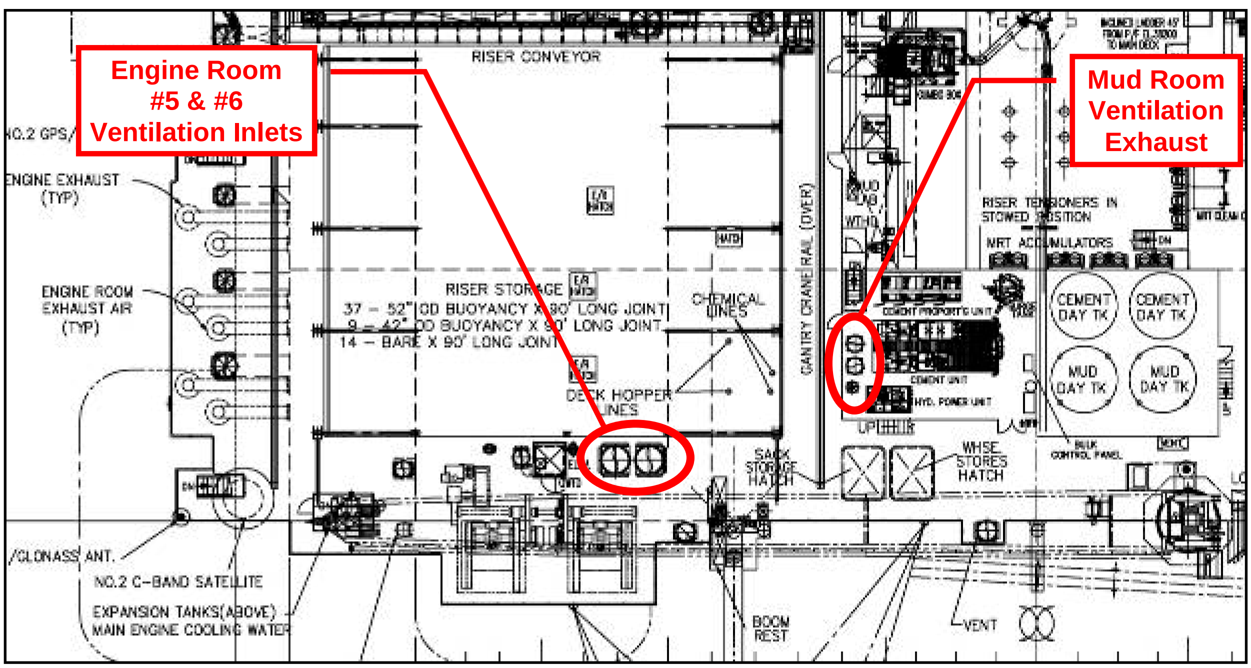


Figure 26. Ventilation Inlets for #5 and #6 Engine Rooms (HRBS-058-000-P0607, rev.5)

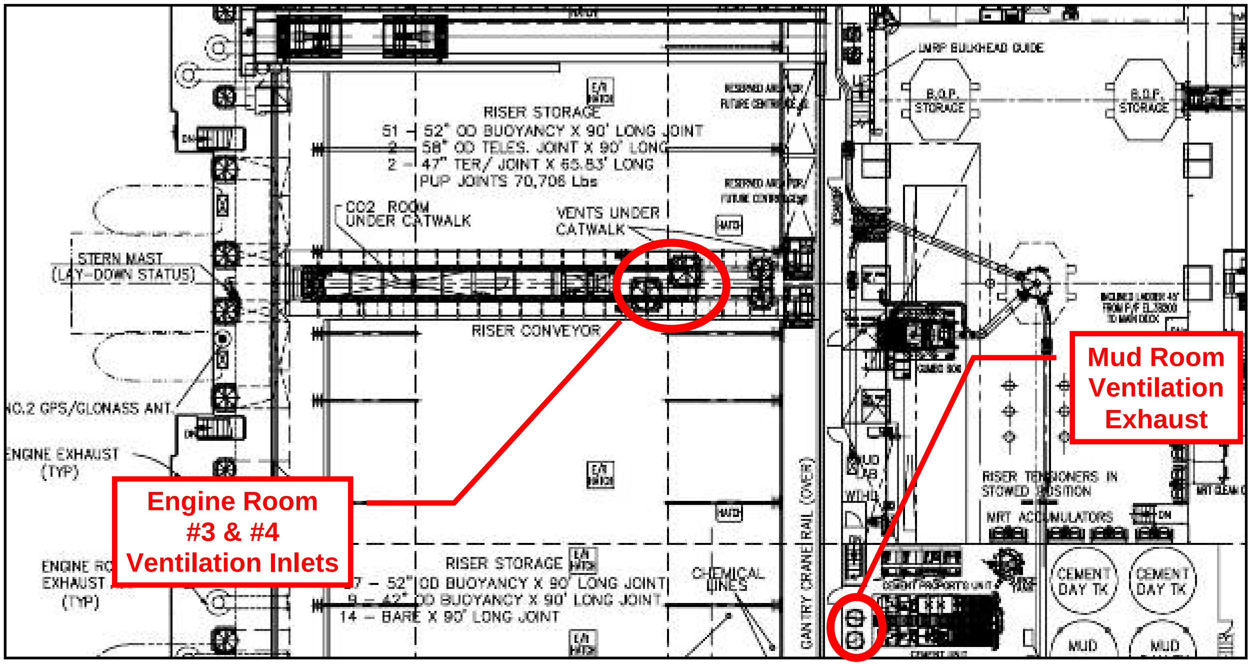


Figure 27. Ventilation Inlets for #3 and #4 Engine Rooms (HRBS-058-000-P0607, rev.5)

The #5 and #6 engine room ventilation system intakes are identified in the photographs provided as Figure 32 and Figure 33. The #3 and #4 engine room ventilation system intakes are identified in the photographs provided as Figure 34 and Figure 35.

As indicated in main deck ventilation arrangement drawing (i.e., Figure 30), there are multiple supply and exhaust fans installed over the main deck area in addition to those called out for engine rooms #3 through #6, with the majority located on the aft end of the deck. Furthermore, as indicated in Figure 4 and Figure 25, each engine has two exhaust stacks located at the aft edge of the main deck. Each supply and exhaust is a momentum source or sink and affects the air flow in its vicinity. Because the number of momentum sources or sinks is limited in FLACS, not all engine exhaust stacks were included in the model. Additionally, low flow rate fans were combined with adjacent larger flow rate fans where appropriate. Table 4 lists the supplies and exhausts (suctions and jets, respectively) included in the FLACS dispersion model. The “leaks” are numbered 1 through 50. Leaks 1, 27, 33, 35, and 48 are not associated with the ship’s air ventilation system; rather, they are the gas release locations associated with the FLACS model. These release points will be discussed in greater detail below.

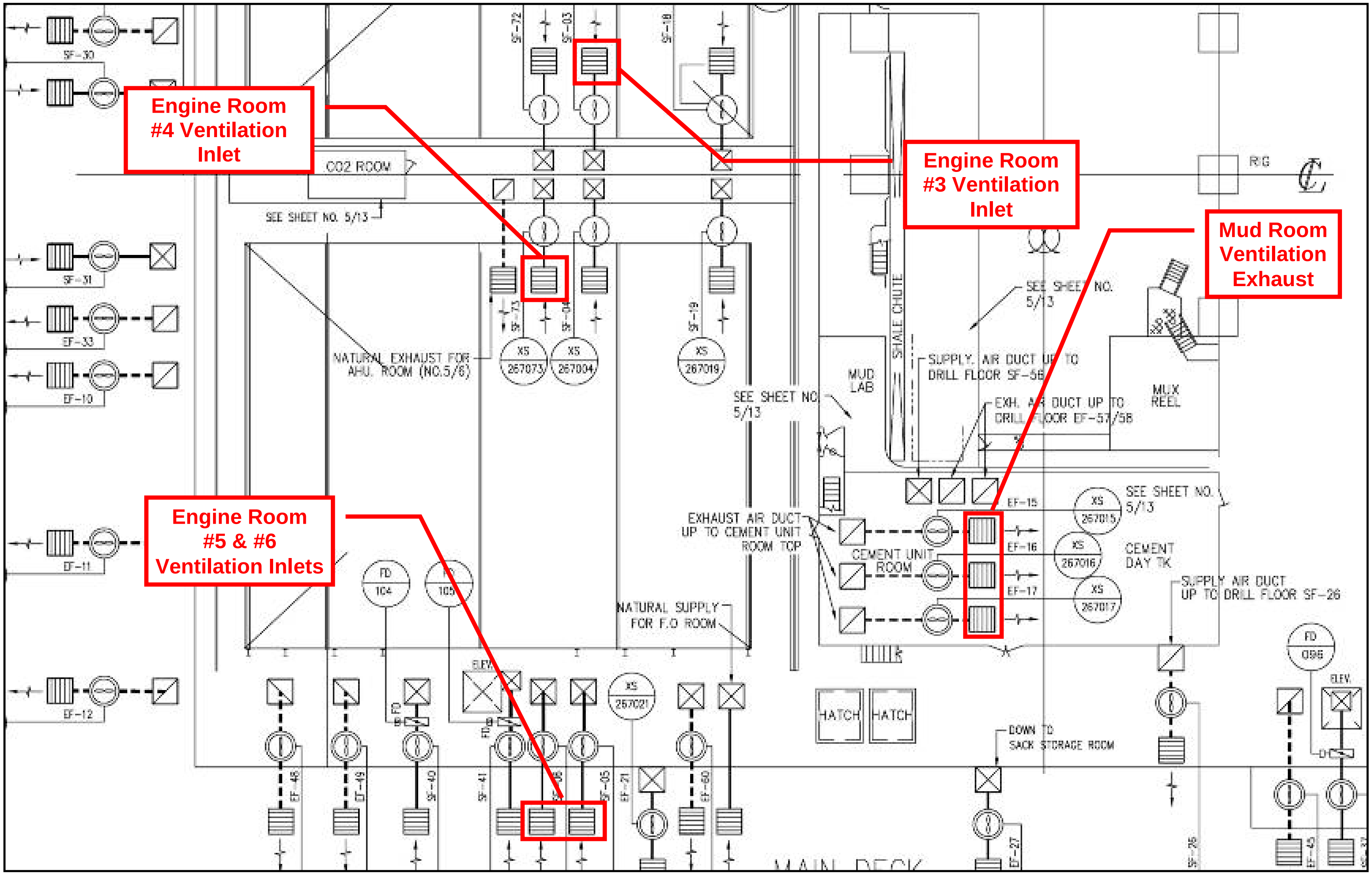


Figure 28. Engine Room and Mud Room Ventilation Fans (HRBS-H68-000-H1010, 6 of 13, rev.2)

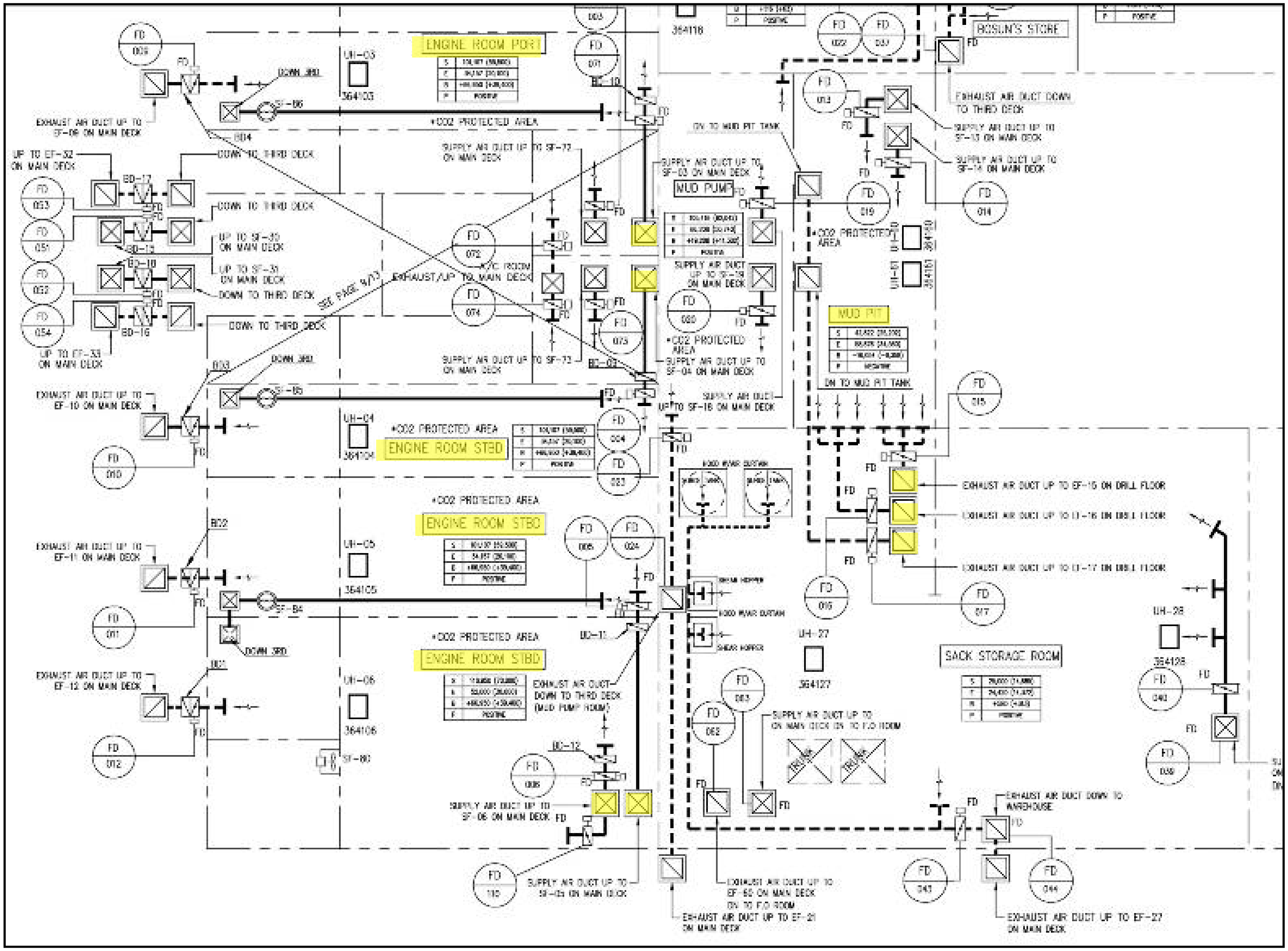


Figure 29. Engine Room and Mud Room Ventilation Fans (HRBS-H68-000-H1010, 7 of 13, rev.2)

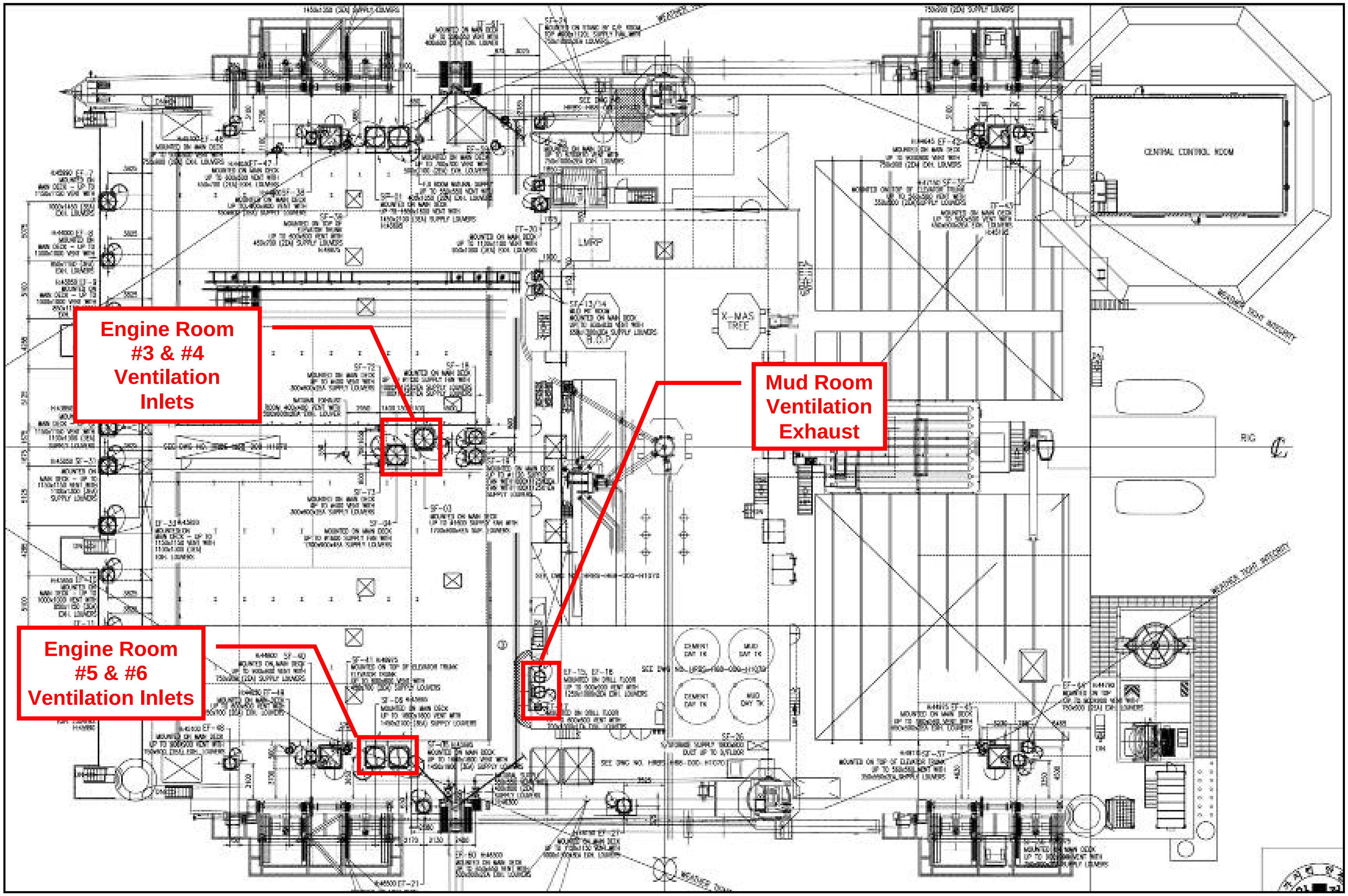


Figure 30. Engine Room and Mud Room Ventilation Fans (HRBS-H68-000-H1060, rev.1)

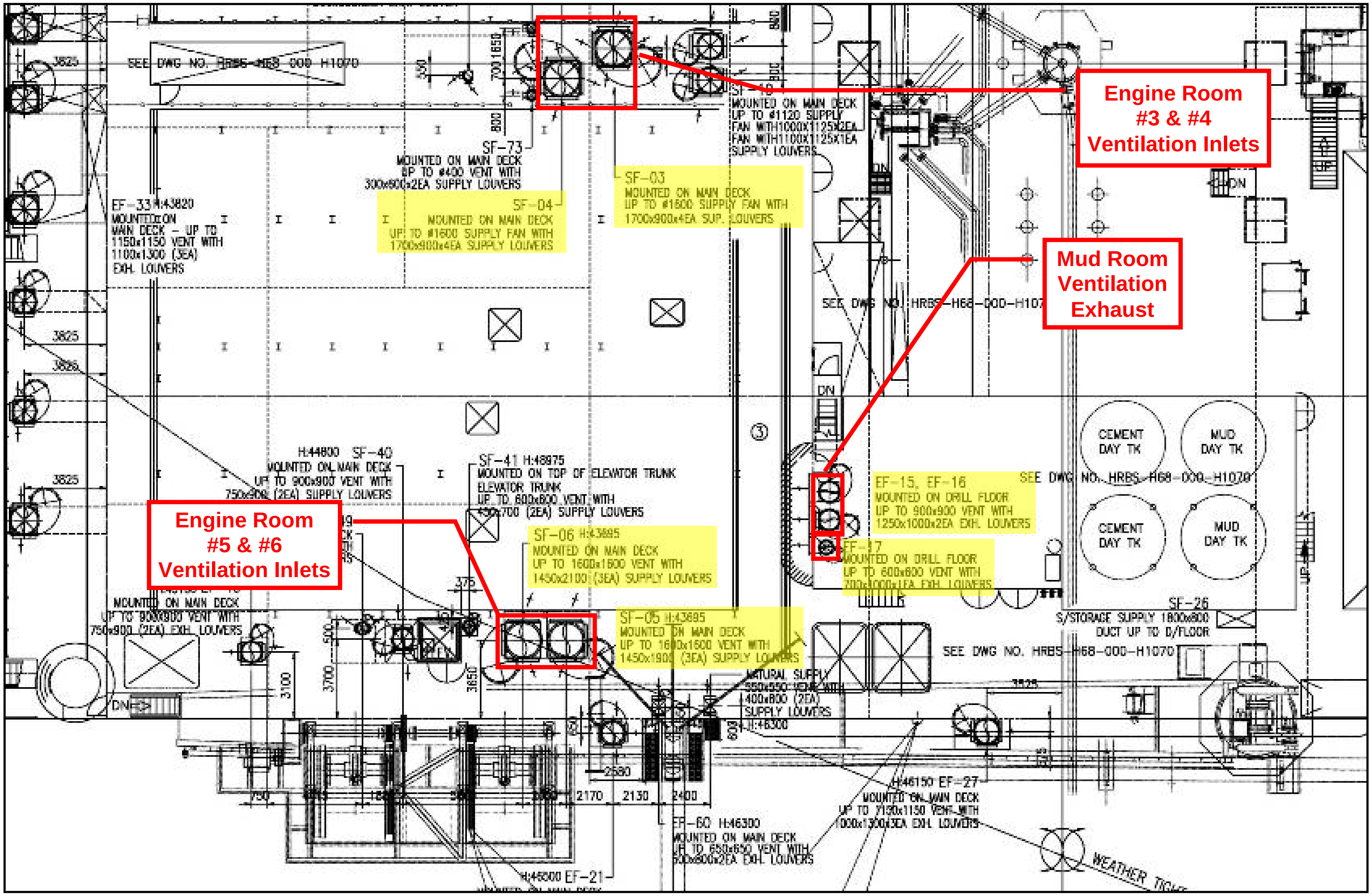


Figure 31. Engine Room Ventilation Fans, Enlarged View (HRBS-H68-000-H1060, rev.1)

Figure 32. Photograph of Aft Starboard Area

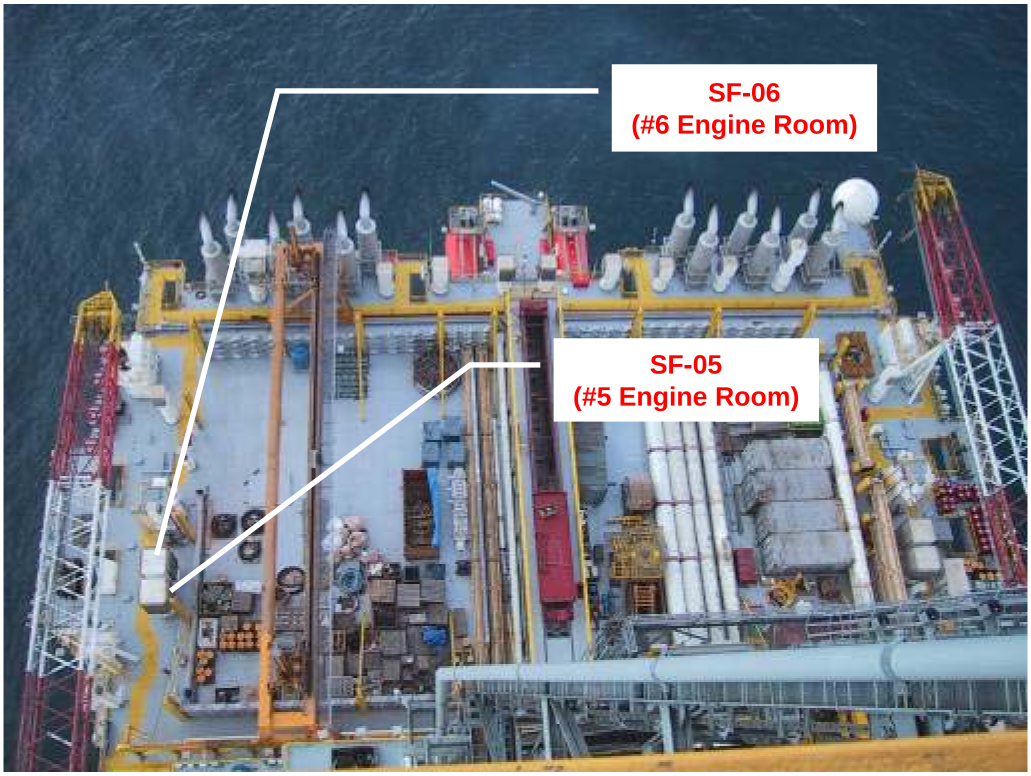


Figure 33. Photograph of Aft End of Ship

Figure 34. Photograph of Aft Mid-Ship Area

Figure 35. Photograph of Aft Mid-Ship Area

Table 4. Ventilation Supplies and Exhausts Included in the FLACS Model

Leak #	Type	Name	Width per Face (m)	Height per Face (m)	# of Faces	Area / Face (m2)	Velocity (m/s)	Mass Flow Rate Air / Face (kg/s)	T (°C)	Face Orientation
1	Jet	**Riser Bore at Drill Floor (Scenario A) or Vacuum Breaker Vent (Scenario B)**								up (A), down (B)
2	Suction	SF-05	1.45	1.9	3	2.76	3.40	11.1	21	p,f,s
3	Suction	SF-06	1.45	2.1	3	3.05	3.62	13.1	21	p,a,s
4	Suction	SF-41	0.45	0.7	2	0.32	4.54	1.7	21	p,s
5	Suction	SF-40	0.75	0.9	2	0.68	7.44	6.0	21	p,s
6	Suction	SF-31	1.1	1.3	3	1.43	3.28	5.6	21	p,f,a
7	Suction	SF-30	1.1	1.3	3	1.43	3.28	5.6	21	s,f,a
8	Suction	SF-34&35	0	0	3	0.85	5.04	4.7	21	p,f,s
9	Suction	SF-04	1.7	0.9	4	1.53	4.59	8.3	21	p,f,s,a
10	Suction	SF-03	1.7	0.9	4	1.53	4.59	8.3	21	p,f,s,a
11	Suction	SF-19	1.1	1.125	3	1.24	3.94	5.8	21	s,f,a
12	Suction	SF-18	1.1	1.125	3	1.24	3.94	5.8	21	p,f,a
13	Suction	SF-13	0.65	1.3	2	0.85	3.52	3.5	21	p,a
14	Suction	SF-14	0.65	1.3	2	0.85	3.52	3.5	21	s,a
15	Suction	SF-36&37	0	0	3	0.87	4.96	4.7	21	a,f,s
16	Suction	SF-38	0.75	0.9	2	0.68	7.44	6.0	21	p,s
17	Suction	SF-39	0.45	0.7	2	0.32	4.54	1.7	21	p,s
18	Suction	SF-01	1.45	2.1	3	3.05	3.62	13.1	21	p,s,a
19	Suction	SF-02	1.45	1.35	3	1.96	4.78	11.1	21	p,s,f
20	Suction	SF-24	0.75	1	2	0.75	7.74	6.9	21	s,f
21	Suction	SF-55	1	1	1	1.00	6.66	7.9	21	p
22	Suction	SF-56	1	1	1	1.00	6.66	7.9	21	a
23	Suction	SF-22	1.5	1.5	1	2.25	4.32	11.5	21	s
24	Suction	SF-26	1	0.75	3	0.75	12.74	11.3	21	s,f,a
25	Jet	EF-60	0.6	0.8	2	0.48	3.02	1.7	21	p,s

Leak #	Type	Name	Width per Face (m)	Height per Face (m)	# of Faces	Area / Face (m2)	Velocity (m/s)	Mass Flow Rate Air / Face (kg/s)	T (°C)	Face Orientation
26	Jet	EF-21	0.85	1.1	4	0.94	3.20	3.5	21	p,s,f,a
27	Jet	**Mud-Gas Rupture Disk Outlet / Diverter Starboard Outlet**								s
28	Jet	EF-48	0.75	0.9	2	0.68	7.16	6.4	21	f,a
29	Jet	EF-12	1	1.45	3	1.45	3.32	5.7	21	p,s,a
30	Jet	EF-11	0.85	1.15	3	0.98	3.23	3.7	21	p,s,a
31	Jet	EF-10	0.85	1.15	3	0.98	3.23	3.7	21	p,s,a
32	Jet	EF-33	1.1	1.3	3	1.43	2.84	9.6	21	p,s,a
33	Jet	**Slip Joint**								up
34	Jet	EF-9	0.85	1.15	3	0.98	3.23	3.7	21	p,s,a
35	Jet	**Mud-Gas Separator Vent**								down
36	Jet	EF-7	1	1.45	3	1.45	3.32	8.2	21	p,s,a
37	Jet	EF-46	0.75	0.9	2	0.68	7.16	5.7	21	f,a
38	Jet	EF-47	0.45	0.7	2	0.32	4.36	1.6	21	f,a
39	Jet	EF-59	0.5	1.1	2	0.55	2.63	1.7	21	p,f
40	Jet	EF-20	0.95	1	3	0.95	4.20	4.7	21	s,f,a
41	Jet	EF-25	0.75	1	2	0.75	5.24	4.7	21	p,a
42	Jet	EF-61	0.4	0.6	2	0.24	2.59	0.7	21	s,a
43	Jet	EF-27	1	1.3	3	1.30	7.19	11.1	21	s,f,a
44	Jet	EF-23	1.5	1.5	1	2.25	3.15	8.4	21	f
45	Jet	EF-57	1	1	2	1.00	4.16	4.9	21	s,a
46	Jet	EF-58	1	1	2	1.00	4.16	4.9	21	s,a
47	Jet	Engine 4	N/A	N/A	N/A	N/A	N/A	N/A	385	a
48	Jet	**Mud Processing System - Mud Pit Room Exhaust**								a
49	Jet	Engine 3	N/A	N/A	N/A	N/A	N/A	N/A	385	a
50	Jet	EF-15,16&17	N/A	N/A	N/A	N/A	N/A	N/A	21	a

p=port, s=starboard, f=forward, a=aft; Suction = Supply Fan, Jet = Exhaust Fan; Natural exhaust vents not included.

4.4 Release Scenario Description

4.4.1 Release Point 1 – Riser Bore at Drill floor

This release location represents a vertical release from the riser bore at the drill floor level. Such a release could occur due to a failure of the diverter seal at the top of the riser just below the drill floor rotary table. Figure 36 shows an elevation view of the ship sectioned through the center as viewed from starboard side (i.e., looking port from the well center). An expanded view from this same drawing of the area near the well center is given as Figure 37. Figure 38 shows the riser at the well center through the drill floor elevation, and additional details showing the rotary table are provided in Figure 39. A photograph of the interior of the moon pool (looking starboard, with the front of the ship to the left) from near the top of the second deck is given as Figure 40. Figure 41 shows the drill string penetrating up to the drill floor through the rotary table, and a photograph showing the top of the drill floor and the rotary table is given as Figure 42.

Release point 1 represents a vertical release without impingement on surfaces above release (i.e., as if the gas can flow through openings in the rotary table). The rotary table opening was taken to be a 1 meter diameter cylindrical penetration with an assumed 60% porosity (i.e., 40% of the opening area was treated as if it were obstructed due to equipment and supporting structure).

Release point 1 was considered in Scenario A only.

4.4.2 Release Point 2 – Mud-Gas Separator (MGS) Vent

This location represents a release of gas from the vent line off the mud-gas separator (aka, the gas buster). A photograph showing this vent line near the starboard-aft support of the derrick is included as Figure 43. Well fluids could be directed to the separator provided that the riser diverter seal holds, and some gas continues to flow to the separator even if the diverter seal partially failed. The vent line terminates at the top of the derrick in a goose-neck configuration (i.e., it is directed downward). The location of the mud-gas separator vent line at the top of the derrick can be seen in the platform elevation views (i.e., Figure 7 through Figure 10), and is highlighted in the platform elevation view given as Figure 44. The vent line diameter is approximately 12 inches (see Figure 49).

Release point 2 was considered in both Scenario A and Scenario B.

4.4.3 Release Point 3 – MGS Rupture Disk / Diverter Starboard Outlet

This release location represents a release of gas had the diverter been lined up to the starboard outlet. As with the MGS vent release scenario (Release point 2), well fluid could be directed from the diverter (provided that the diverter seal holds) to either a port or starboard overboard line. It is understood the port diverter would not have been activated due to the presence of a support vessel on the port side of the Deepwater Horizon. The location of the mud-gas rupture disk and Diverter outlet is shown on a main deck plot plan in Figure 45, with an expanded view of the outlet location given in Figure 46. The Diverter outlet diameter is approximately 14 inches and the MGS Rupture Disk outlet is a 6-inch line running above the diverter starboard line (see Figure 49).

Release point 3 was considered in both Scenario A and Scenario B In Scenario A, flow from both the MGS Rupture Disk and Diverter outlets were combined into a single flow (see Figure 52). In Scenario B, a specific location (above the Diverter outlet) had been identified for the rupture disk outlet. Further, the Diverter outlet flow contribution was reduced to zero (see Figure 53.)

4.4.4 Release Point 4 – Slip Joint

The release location represents a release of gas from a failed packer seal on the telescopic joint (i.e., the "slip joint"). Such a release would be located beneath the ship hull (i.e., under the bottom of the third deck) along the drilling riser. Figure 47 provides a drawing of a telescopic joint with the location of the packer seal highlighted, and Figure 48 shows a telescopic joint within a drilling riser system (the telescopic joint label is called out and the rig floor elevation is noted in this figure).

The vertical separation between the bottom of the 3rd deck and the packer seal is not known with certainty at this time, and a separation distance of 2 meters was assumed for the purposes of this analysis. The packer seal failure was represented by a single hole with a diameter of seven inches, which gives the same leak area as a one-half inch annular gap around a 24-inch cylinder. The release was represented as being directed upward vertically.

Release point 4 was considered in both Scenario A and B.

4.4.5 Release Point 5 - Mud Processing System – Mud Pit Room Exhaust

This release location represents a release of gas into the mud room mixing with the mud room ventilation air flow, with the subsequent mixture flowing out of the mud room exhaust vents onto the aft deck. This scenario is meant to characterize the flammable gas cloud which could develop outside of the mud room due to a release of gas from the drilling mud transferred from the gas buster or diverter into the mud room.

The mud room exhaust vents were shown in Figure 26 through Figure 31. The vents are located on top of the cement room and are directed aft. As noted earlier, the total mud room exhaust flow (i.e., louver) area is 5.7 m^2 (61 ft^2) and the total mud room ventilation air discharge rate is 34,650 scfm. A release point was placed adjacent to the mud room ventilation exhaust to account for flammable gas release through the mud room exhaust vents.

The actual dispersion and mixing of gas within the mud room was not modeled since, for the cases examined, it is expected that the composition of the exhaust would quickly approach the equilibrium well-mixed condition.

Release point 5 was considered in both Scenario A and Scenario B.

4.4.6 Release Point 6 – MGS Vacuum Breaker

This release point is the outlet of a 6-inch line which is connected to the 10" MGS liquid outlet line going to the first series of Mud System tanks, i.e. Gumbo and Trip (see Figure 49). The 6" vacuum breaker line is intended to prevent back flow via siphoning from the Mud System tanks into the MGS. The anti-siphon effect is derived from the vacuum breaker being open to the atmosphere at its discharge point. The MGS Vacuum Breaker discharge is located on the aft-starboard derrick support leg at approximately 23 meters above the main deck rig floor (see Figure 43) and is directed downwards (i.e. gooseneck outlet).

Release point 6 was considered in Scenario B only.

4.4.7 Scenario A Release Sequence

BP provided the Scenario A release rate plot shown in Figure 50. The plot depicts the estimated flow of gas as a function of time through the mud system, a combination of the 10" pipe leading to the Mud Pit Room and the 6" pipe leading to the diverter starboard outlet, labeled as 'Gas Out 10" (and 6")', the mud-gas separator vent, labeled as 'Gas out vent-line', the riser, a combination of gas flow out the top of the riser at the drill floor and the slip joint, labeled as 'Gas up riser', and at very late times, the gas flowing out the drill pipe, labeled as 'Gas out DP'. The plot indicates that the release event begins with increasing gas flow through the mud system. After about 60 seconds, gas begins to flow out of the mud-gas separator vent. Another 30 seconds after this, there is a spike as gas begins to flow out of the slip joint and the riser bore at the drill floor. Figure 51 shows the pressure below the diverter corresponding to this release scenario.

Figure 50 and Figure 51 were used to construct the release source parameter specifications listed in Table 5. Nine release phases are shown. The overall release scenario was set to last for 8.5 minutes. A total of 1.2 MMscf of gas is estimated to be released over this duration. Figure 52 displays the data shown in Table 5 graphically. This figure depicts the gas released as a function of time through each of the release points described above. Flow through the mud system is estimated by dividing flow based on the relative flow areas of the pipe leading to the mud-gas rupture disk outlet (6" pipe) and the pipe leading to the mud pit room (10" pipe). Based on this split, 26% of the flow is directed in the model through the diverter starboard outlet and 74% is directed to the mud pit room. 90% of the flow through the riser is taken to be out of the top of the riser bore at the drill floor with the remaining 10% flowing out of the slip joint beneath the moon pool. Note that the total gas flow is plotted on the right vertical axis.

4.4.8 Scenario B Release Sequence

The second simulated release scenario provided by BP was intended to focus on the initial potential dispersion of a well flow rate partially restricted by potential circumstances such as a closing BOP, debris obstructions, etc. Additional information regarding equipment design limits, relief points, and set points were also incorporated. For modeling efficiency and consistency with the analysis focus, the duration of this scenario was limited to six minutes. A total of 0.33 MMscf of gas was emitted over this time period. In the actual event, gas flow continued beyond the modeled six minutes. The Scenario B release source parameter specifications are given in Table 6. Five release points are considered: the MGS vent, MGS rupture disk (6" outlet above the Diverter starboard 14" outlet), slip joint, mud pit room exhaust, and the MGS vacuum breaker vent. The flow rate of flammable gas from each release point was ramped linearly over each phase. At the end of Phase 3 shown in Table 6, gas flow from all five release points was ramped linearly to zero over the following two seconds. Note that in Scenario B the release is not sequential as it was in Scenario A. Rather, flammable gas is released at different rates simultaneously from all five release points. The flammable gas release rate as a function of time for each location is shown graphically in Figure 53. Note that the total gas flow is plotted on the right vertical axis. It should be noted that the total release rate for Scenario B is roughly 20% of that for Scenario A.

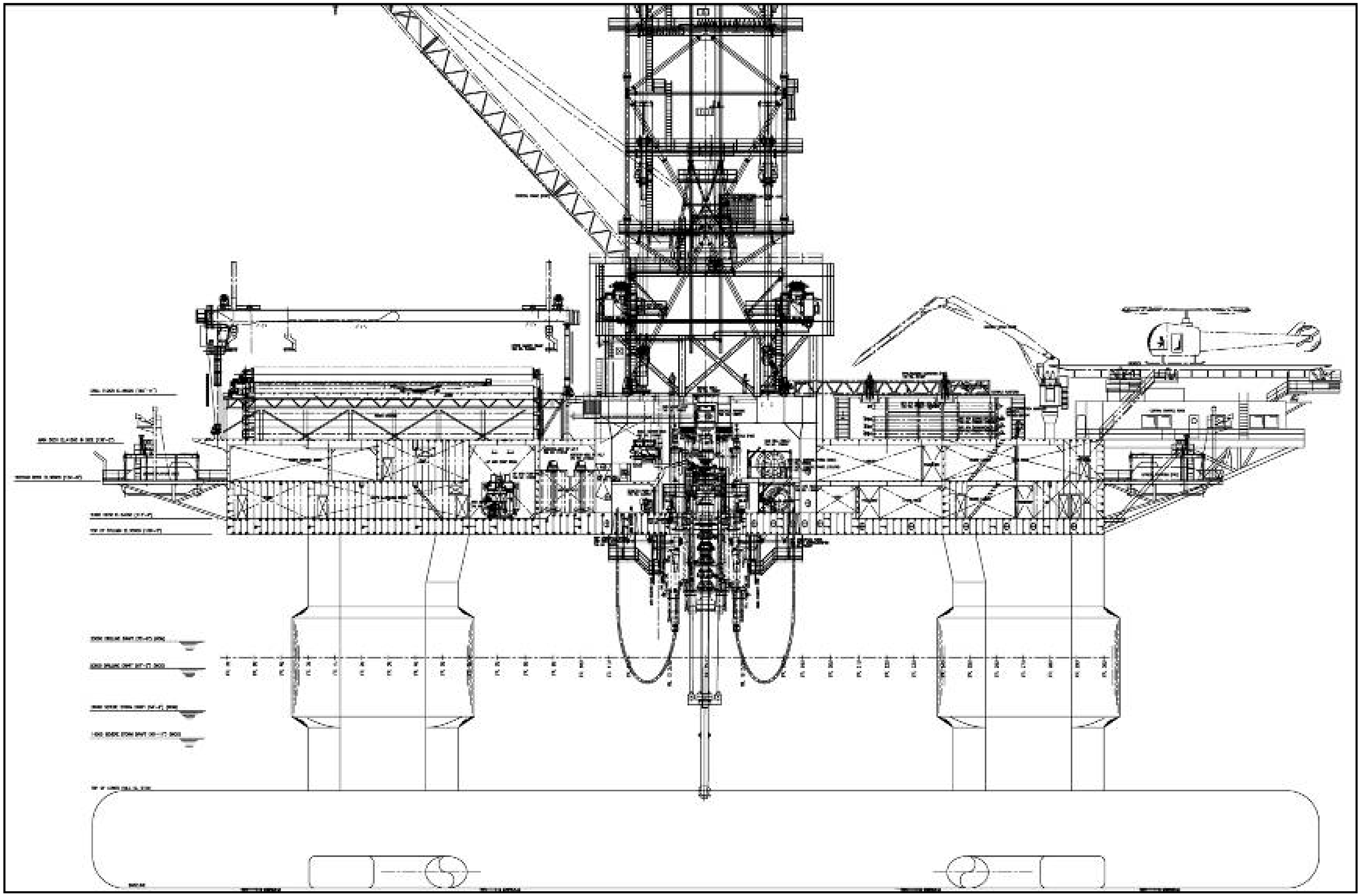


Figure 36. Ship Elevation View through Well Center (HRBS-M56-U00-H3101, rev.0)

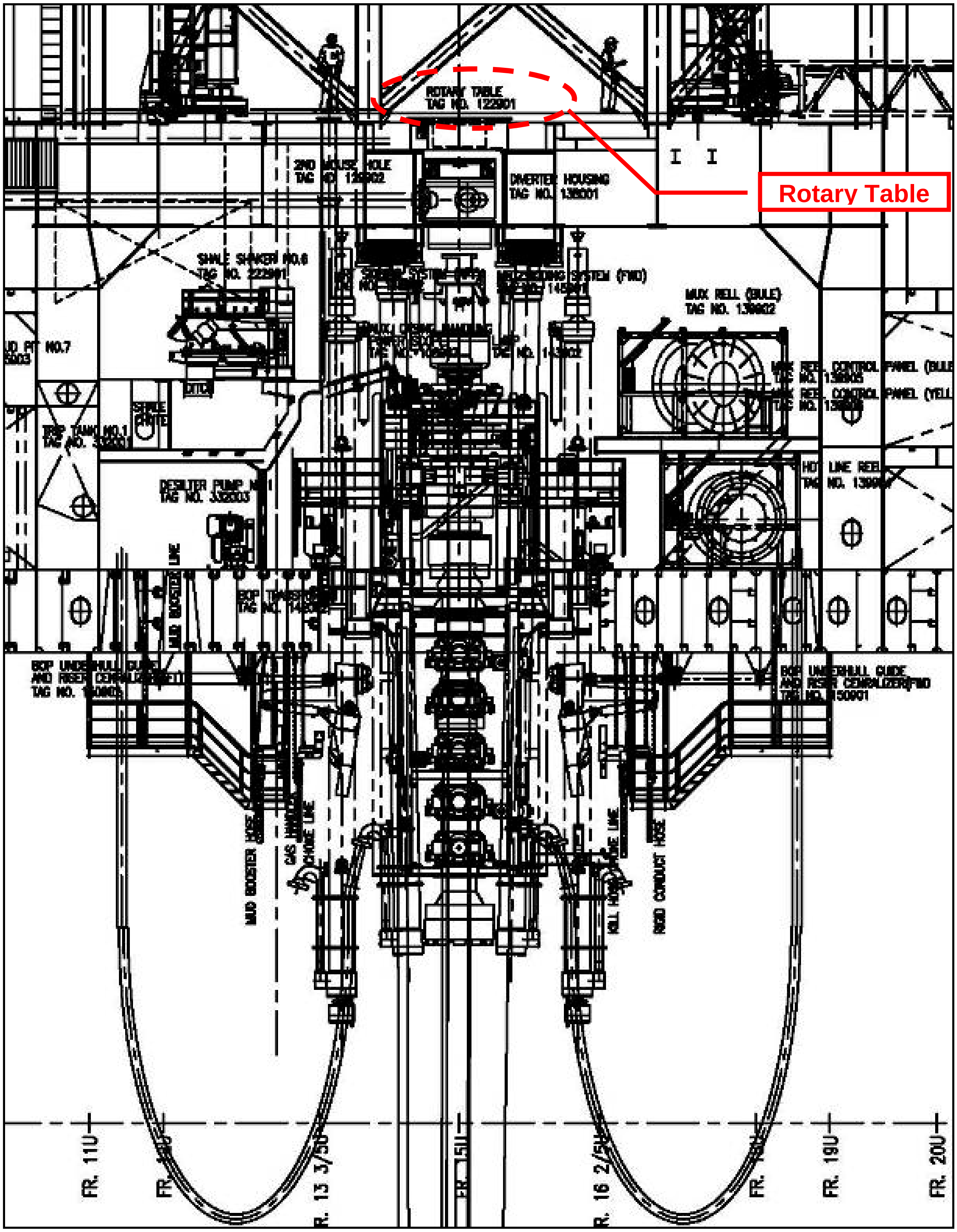


Figure 37. Expanded View near Well Center (HRBS-M56-U00-H3101, rev.0)

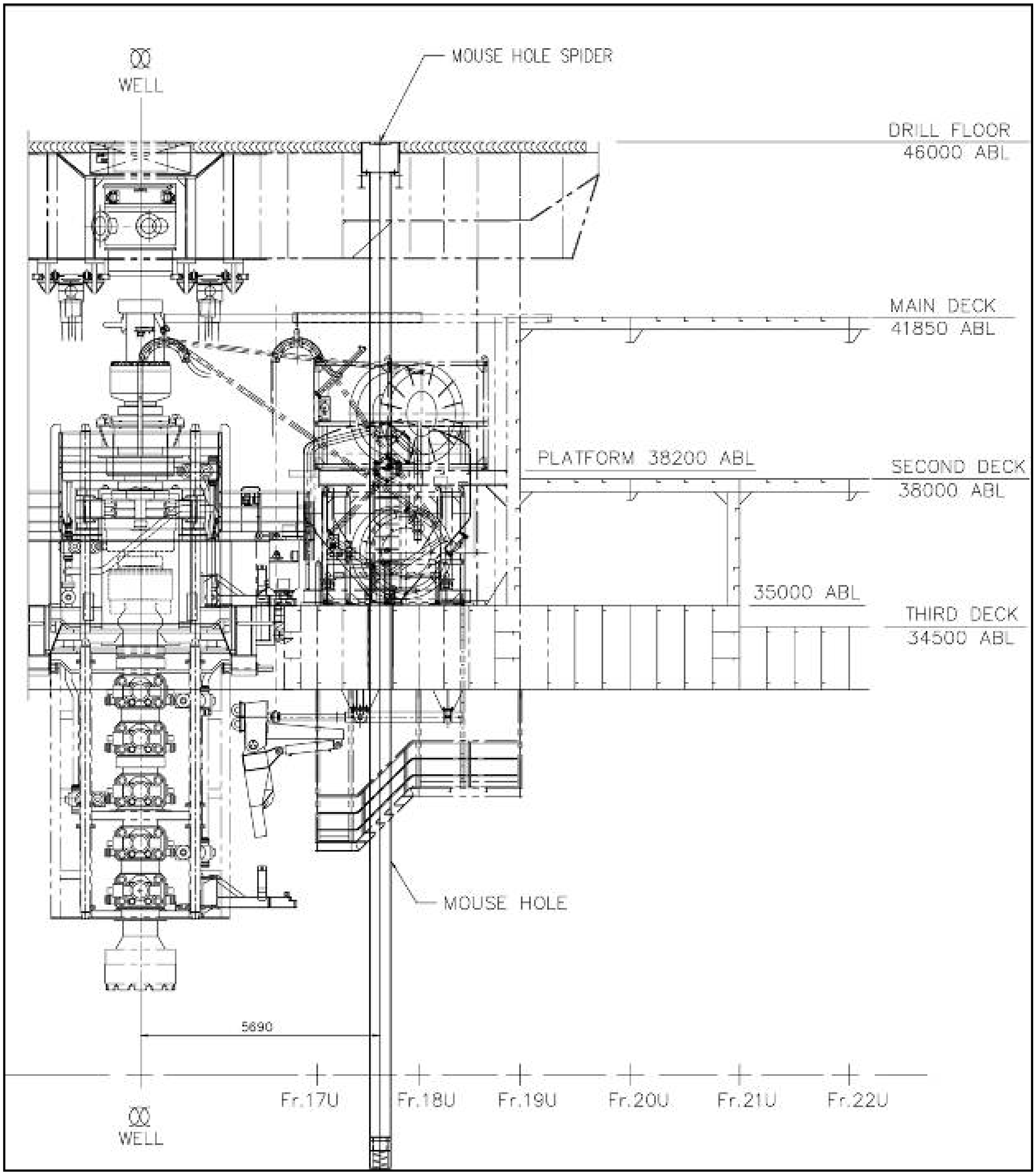
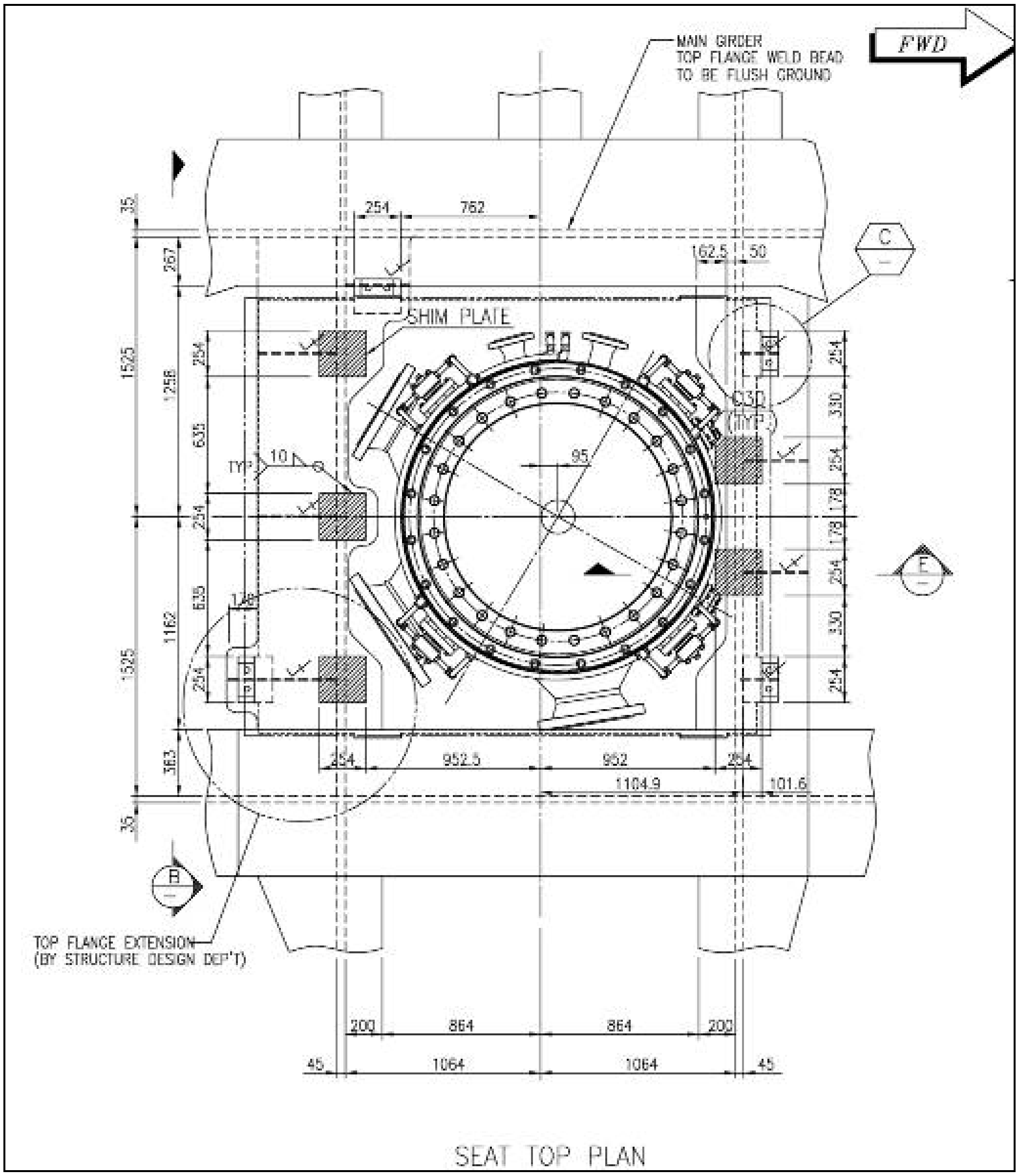


Figure 38. Riser at Well Center through Drill Floor (HRBS-M69-U01-H7005, rev.0)



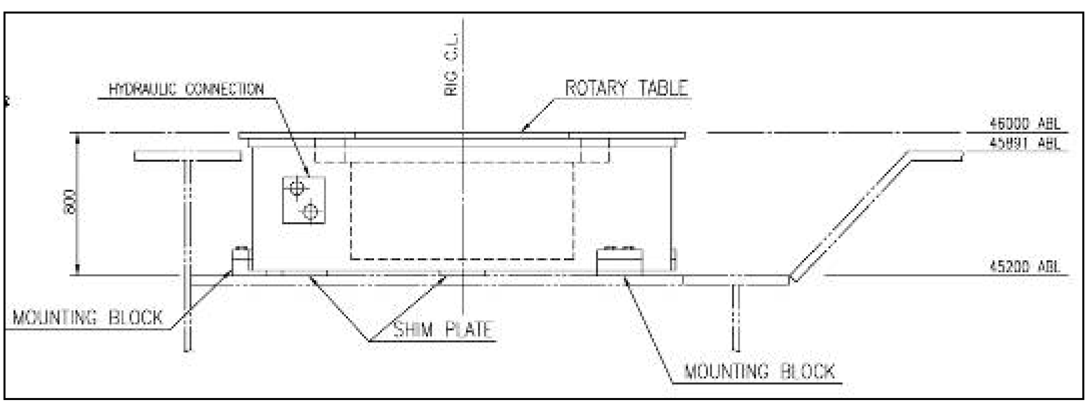


Figure 39. Rotary Table Details (HRBS-M69-U01-H7004, rev.0)

Figure 40. Moon Pool Interior (Looking Starboard)

Figure 41. Bottom of Drill Floor (Looking Up)

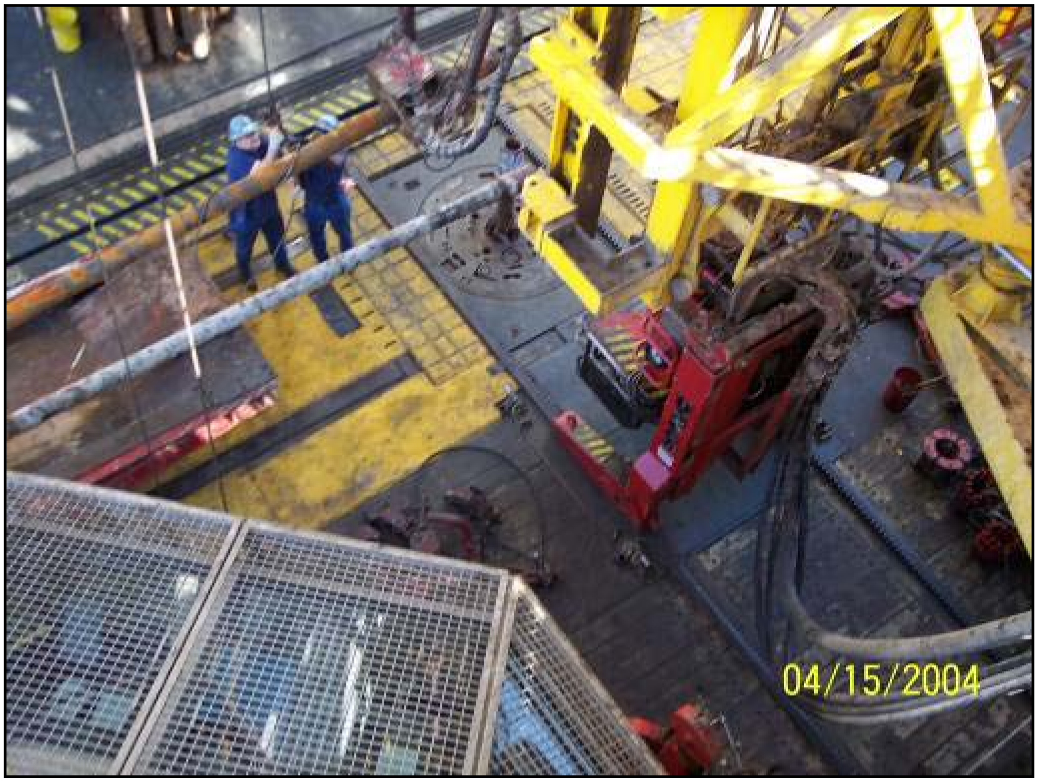


Figure 42. Top of Drill Floor (Looking Down)

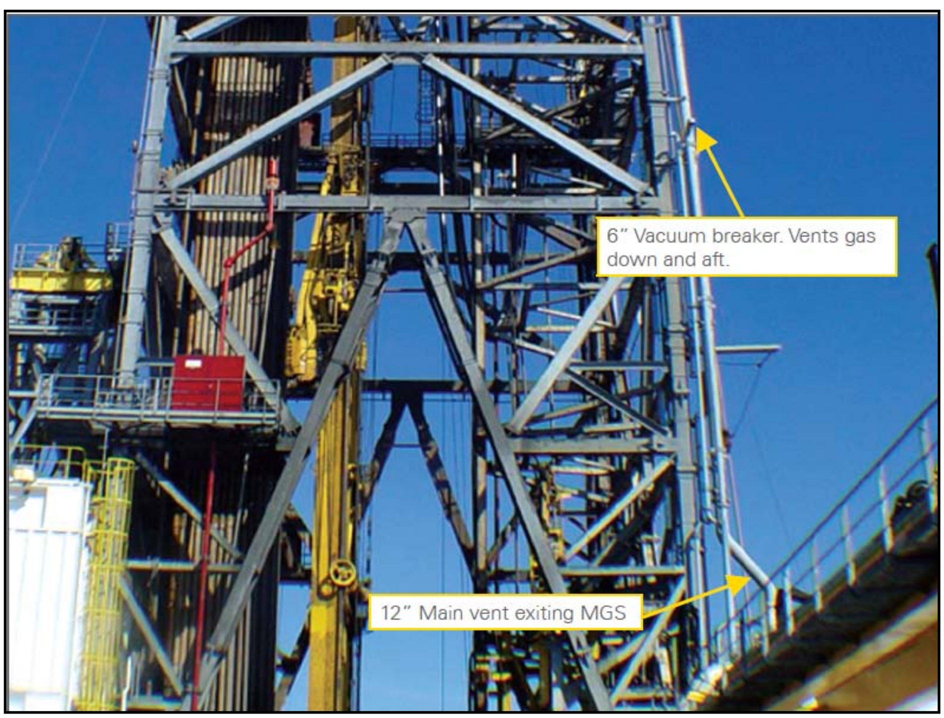


Figure 43. 12" Main Vent Exiting the MGS and the 6" Vacuum Breaker Vent

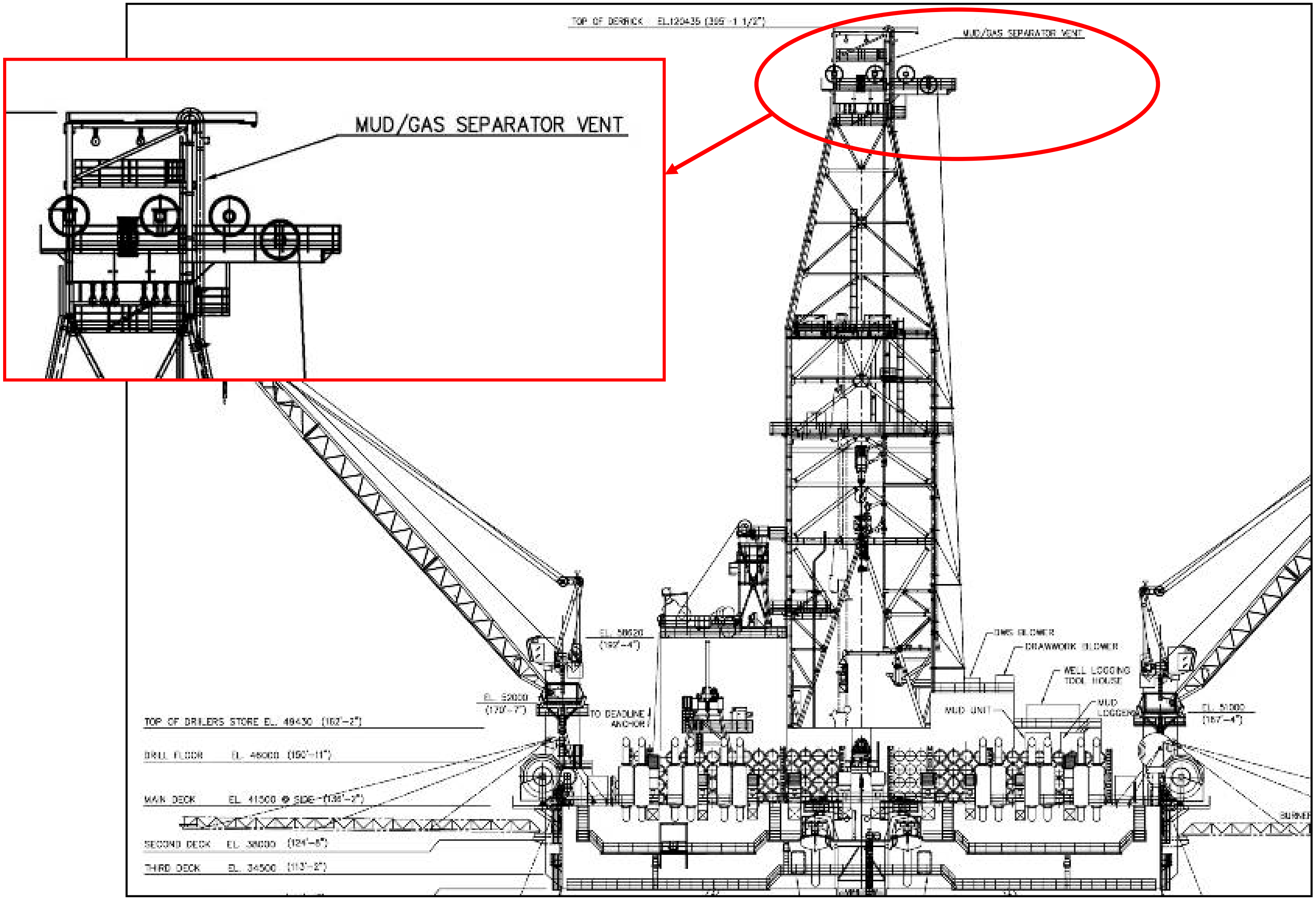


Figure 44. Mud-Gas Separator Vent Line, Stern Elevation (HRBS-058-000-P0605, rev.5)

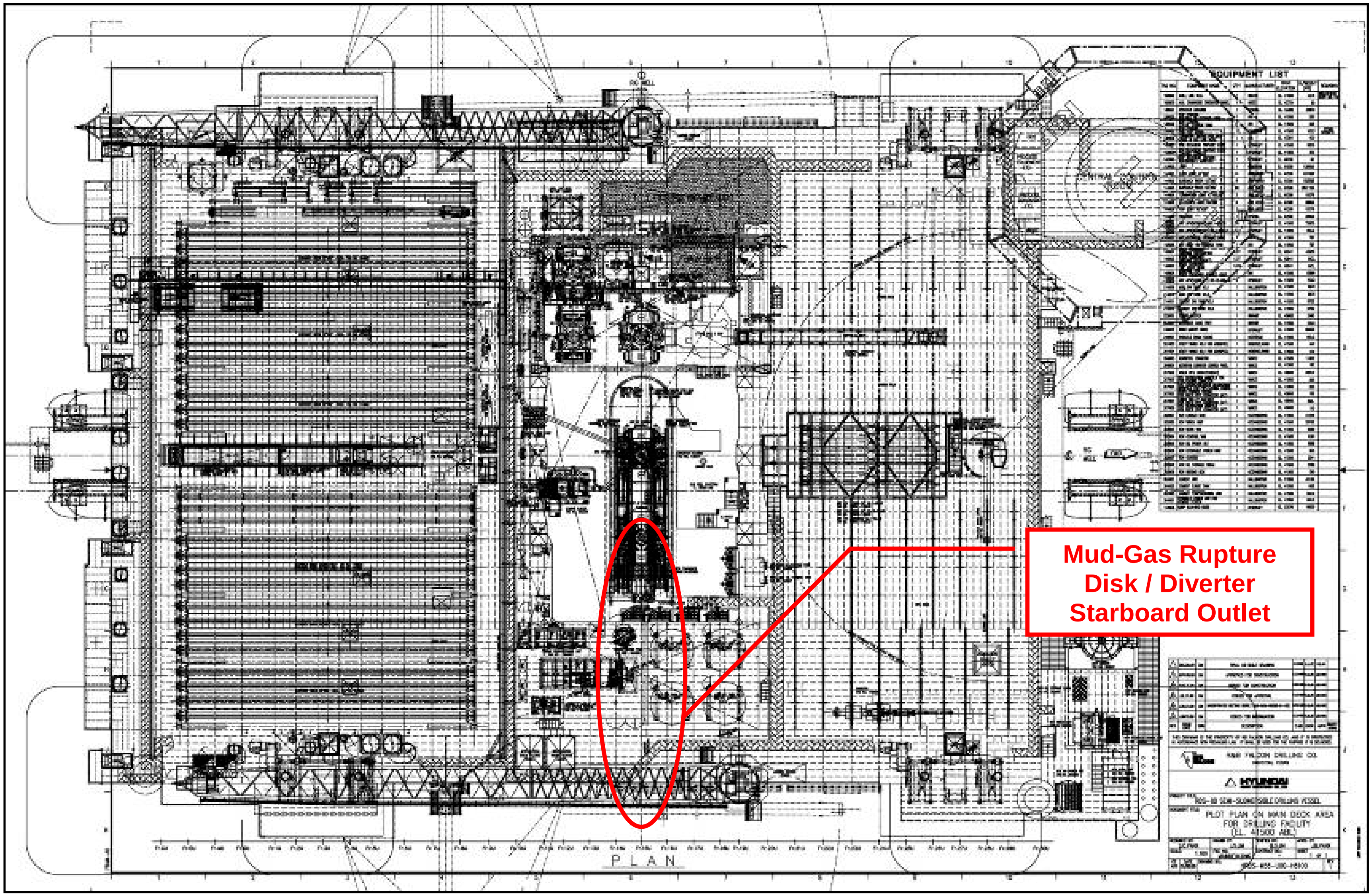


Figure 45. Mud-Gas Rupture Disk Outlet, Main Deck Plot (HRBS-M56-U00-H6100, rev.1)

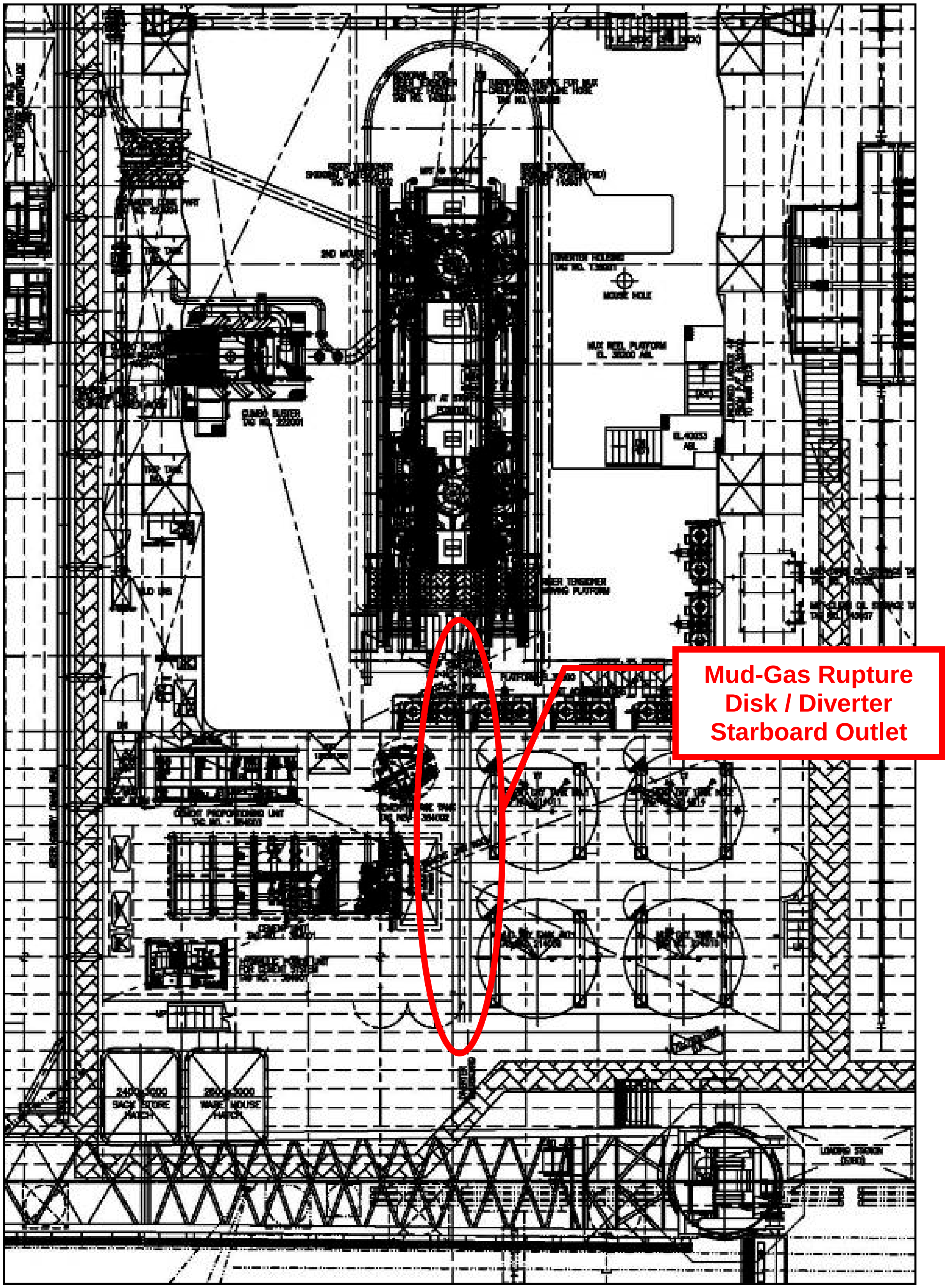


Figure 46. Mud-Gas Rupture Disk Outlet, Expanded View (HRBS-M56-U00-H6100, rev.1)

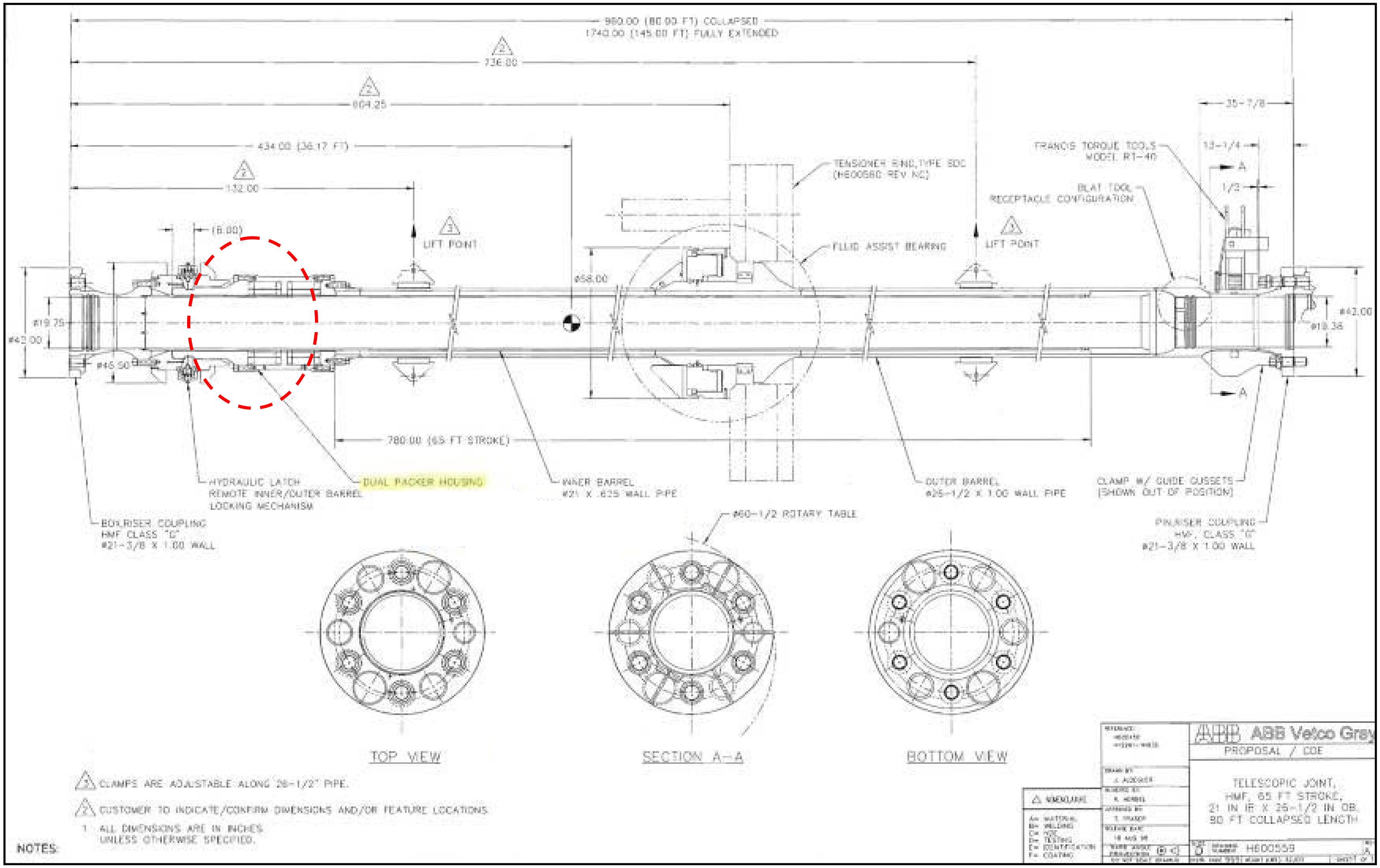


Figure 47. Telescopic Joint and Packer Seal (ABB Vetco Gray drawing H60059, rev.A)

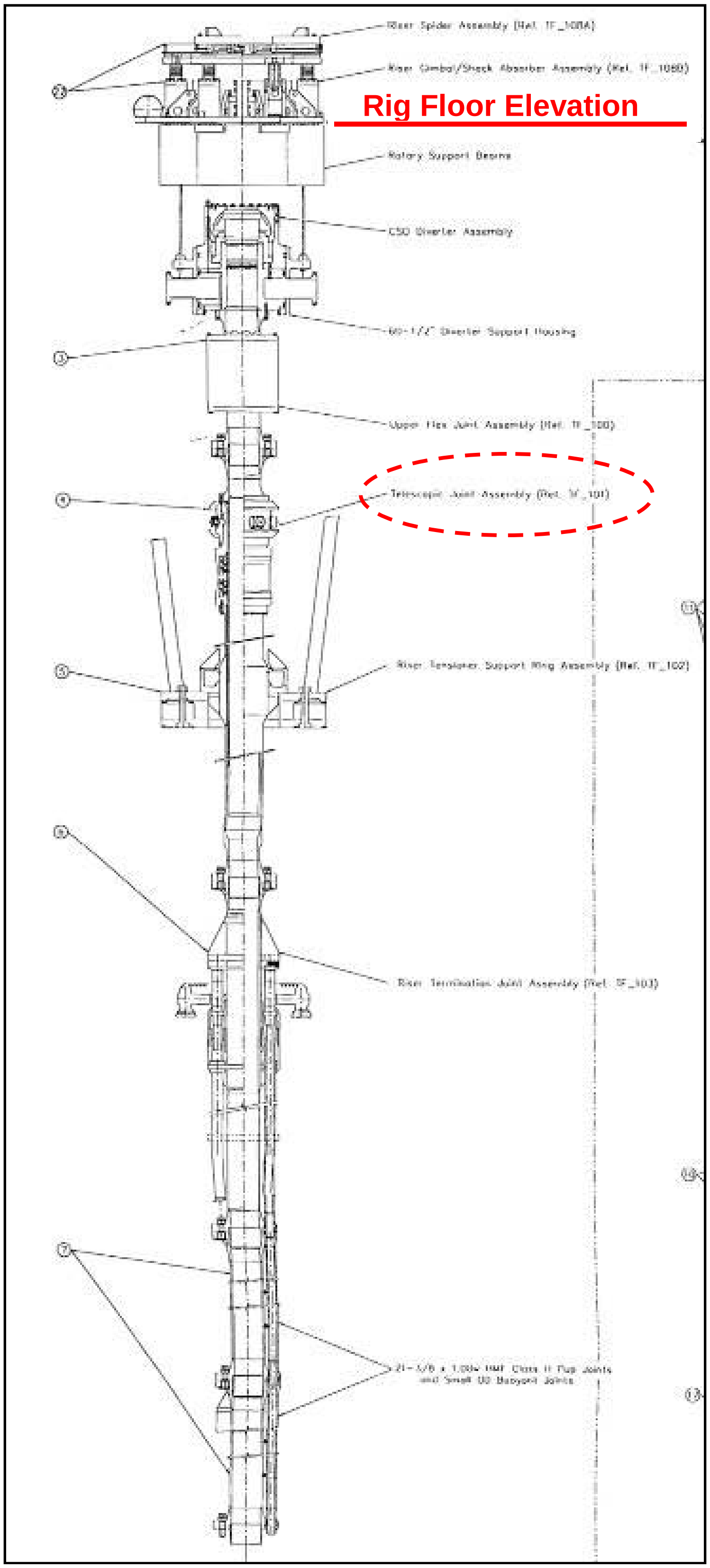


Figure 48. Telescopic Joint within Riser System (ABB Vetco Gray drawing TF_113)

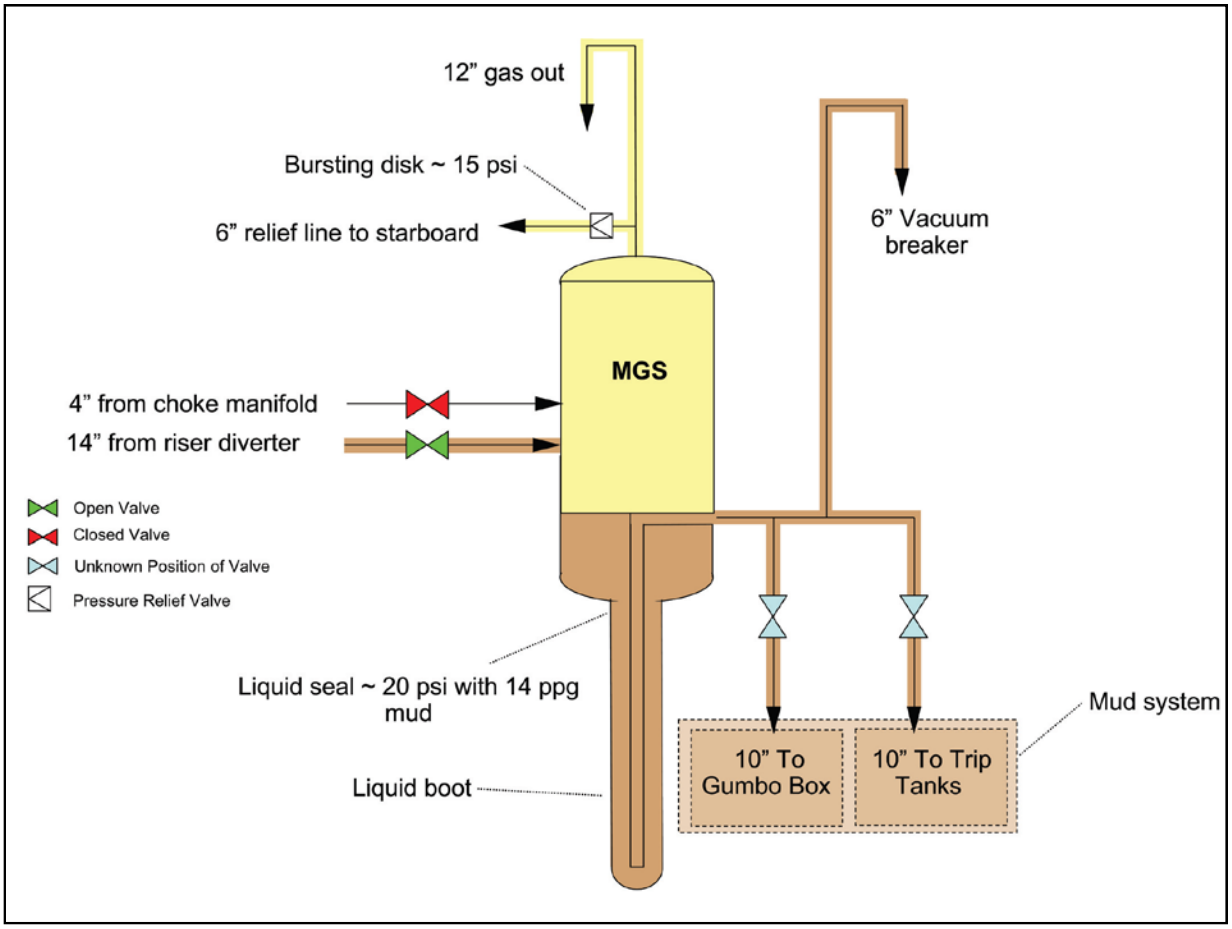


Figure 49. Schematic Drawing of Mud Gas Separator

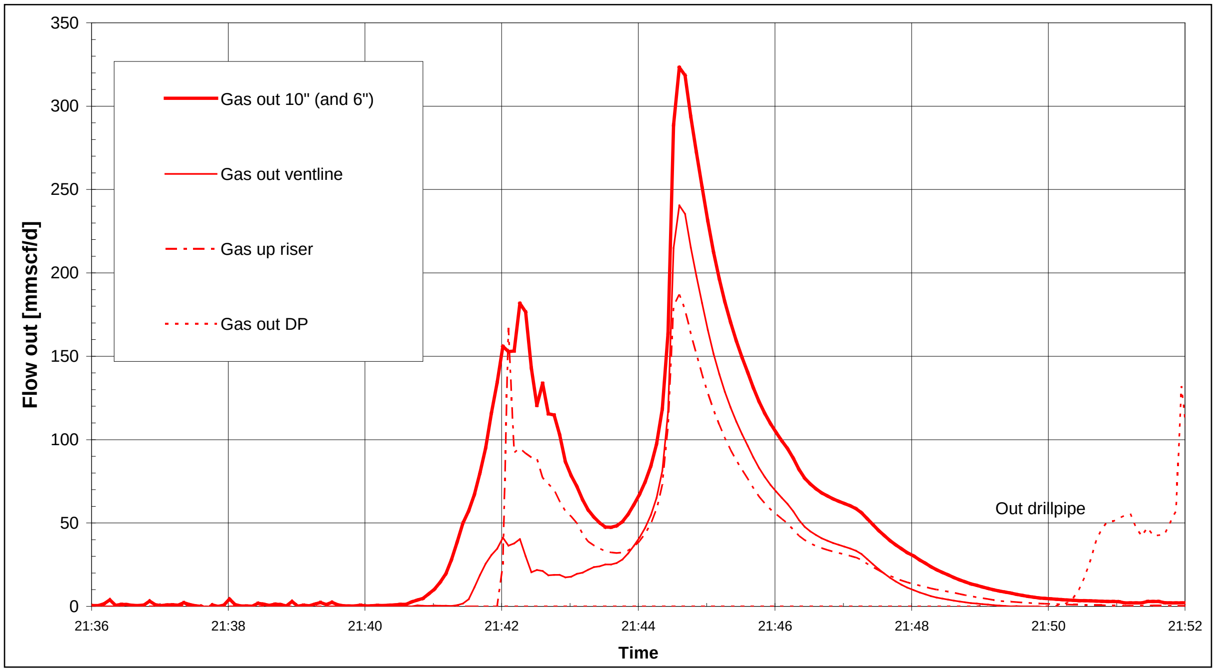


Figure 50. Flow of Gas as a Function of Time through All Release Locations (Scenario A)

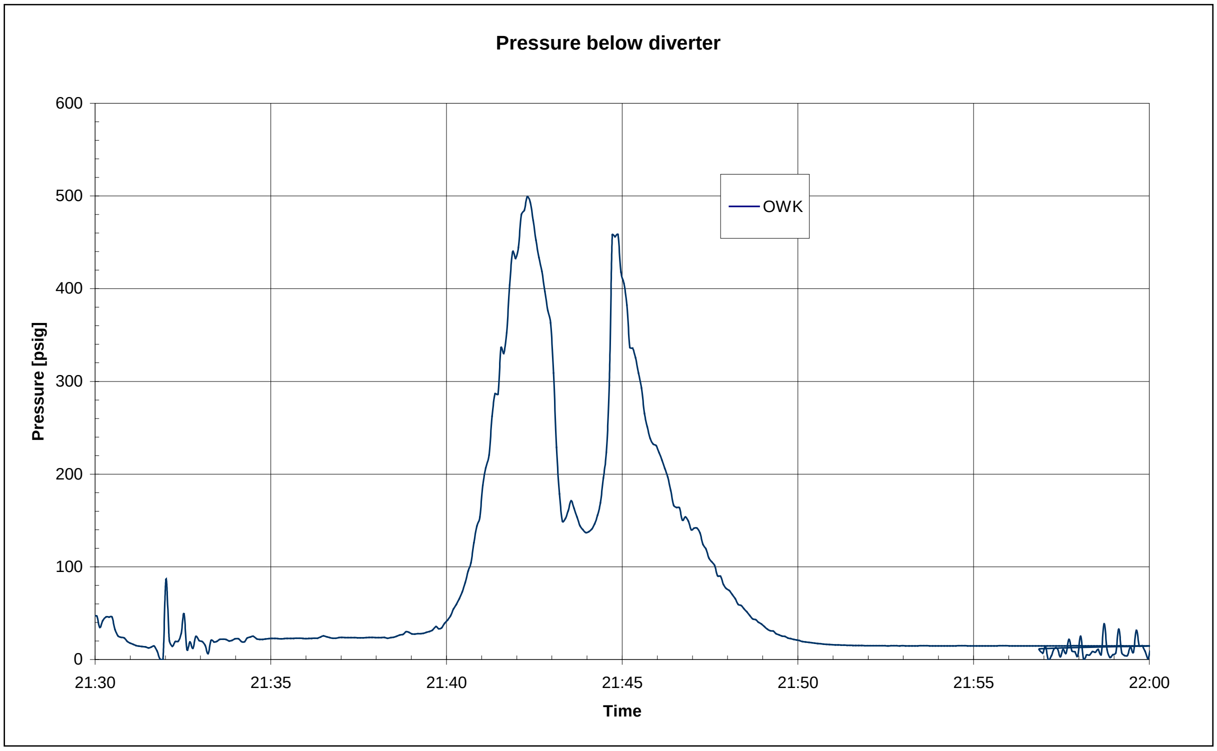


Figure 51. Pressure Below the Diverter Corresponding to the Release Shown in Figure 50 (Scenario A)

Table 5. Scenario A Release Source Parameter Specifications

Phase No.	Time at Start of Phase	Phase Duration (min.)	Flow Rate Over Phase (MMSCF/d)	Path (through which gas released)	Pressure – riser @ diverter (psig)
1	21:40:30	0.5	0 - 10	Mud System	60-300
2	21:41:00	0.5	10 - 50	Mud System	60-300
3	21:41:30	0.5	50 - 160	Mud System	300 - 340
			0 - 40	MGS Vent	
4	21:42:00	0.5	160	Mud System	340 - 500
			40 - 20	MGS Vent	
			150 - 75	Riser	
5	21:42:30	1	160 - 50	Mud System	500 - 160
			20	MGS Vent	
			75 - 30	Riser	
6	21:43:30	0.5	50	Mud System	160 - 460
			20 - 40	MGS Vent	
			30 - 40	Riser	
7	21:44:00	0.6	50 – 320	Mud System	160 - 460
			40 - 240	MGS Vent	
			40 - 180	Riser	
8	21:44:36	1.4	320 - 100	Mud System	460 - 25
			240 - 60	MGS Vent	
			180 - 50	Riser	
9	21:46:00	3	100 - 10	Mud System	460 - 25
			60 - 5	MGS Vent	
			50 - 2	Riser	

Table 6. Scenario B Release Source Parameter Specifications

Phase No.	Time at Start of Phase	Phase Duration (min)	Flow Rate over Phase (MMSCF/d)				
			Mud Pit Room	MGS Vent	Vacuum Breaker Vent	MGS Rupture Disk	Slip Joint
1	21:40:30	2	0 to 8	0 to 8	0 to 4	0 to 4	0 to 8
2	21:42:30	2	8 to 38	8 to 38	4 to 19	4 to 19	8 to 38
3	21:44:30	2	38 to 25	38 to 25	19 to 13	19 to 13	38 to 25

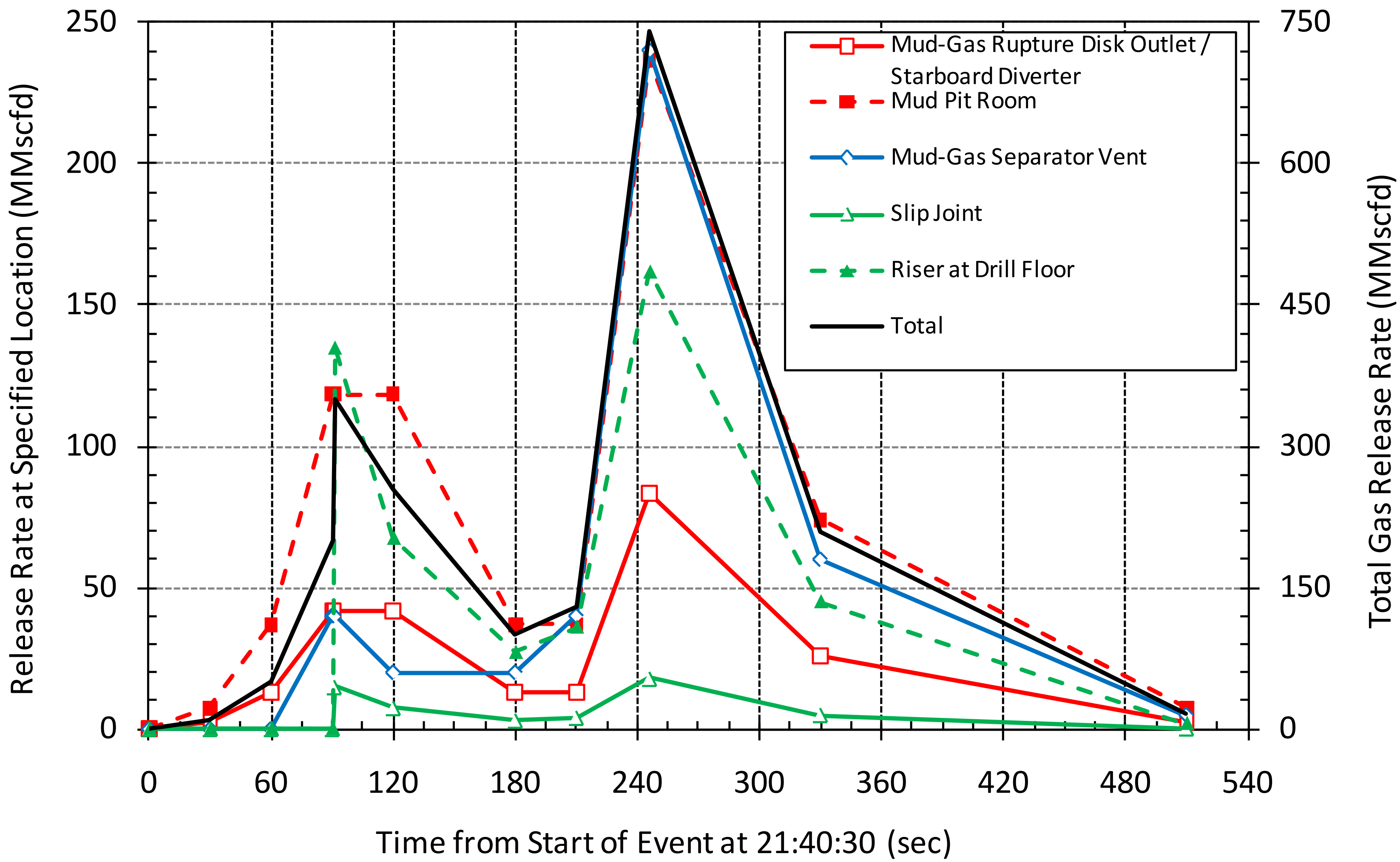


Figure 52. Gas Flow Rate (MMscfd) History for Each Release Point (Scenario A)

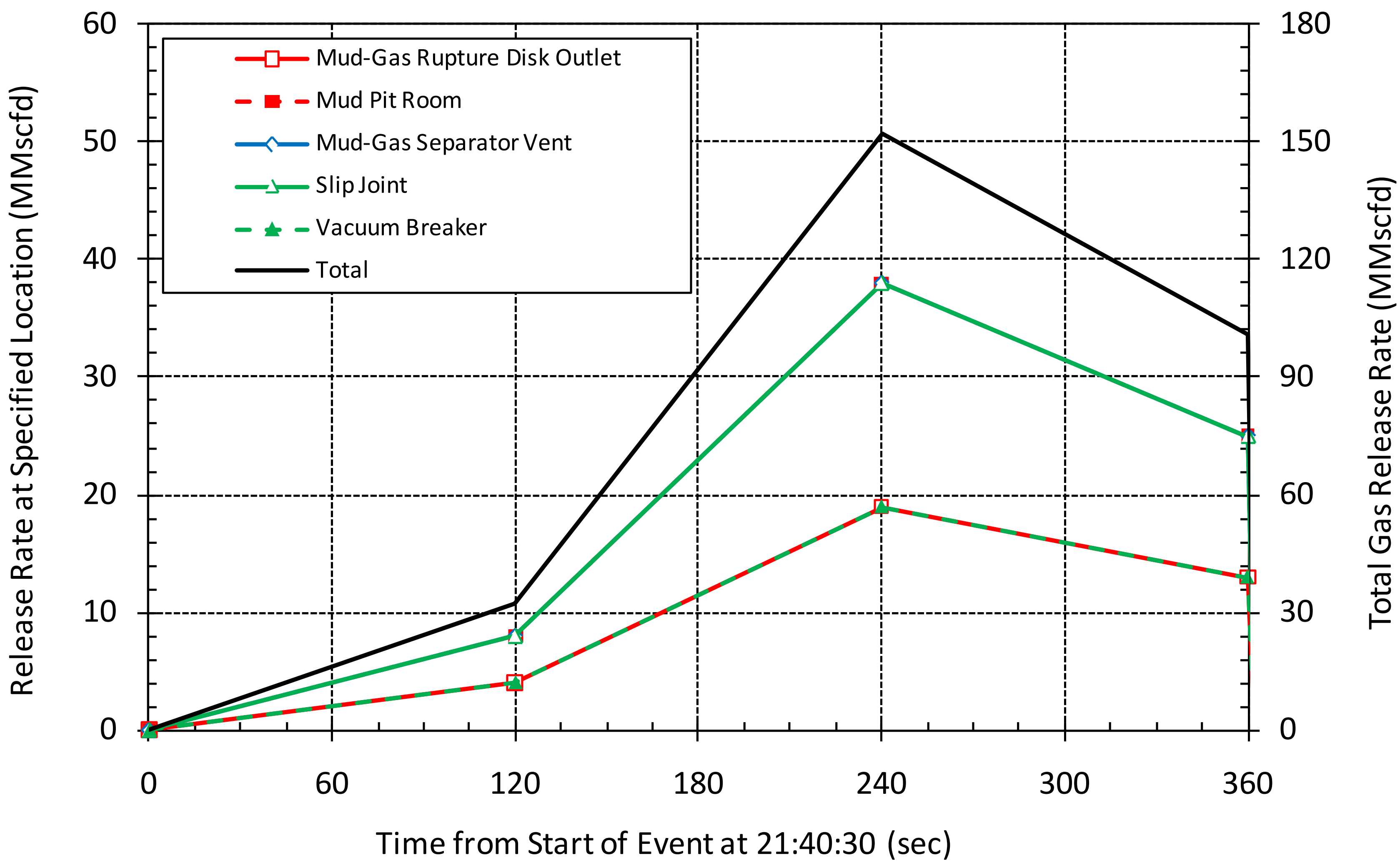


Figure 53. Gas Flow Rate (MMscfd) as a Function of Time from Each Release Point (Scenario B)

5 FLACS MODEL DESCRIPTION

Figure 54 shows an overview of the solid model as viewed from the starboard aft corner of the MODU. Figure 55 and Figure 56 show an overview of the solid model as viewed from the aft and forward ends respectively. The model includes the hull, the main deck structure, the key buildings in the vicinity of the drill floor, the helideck, the catwalk aft of the drill floor, the partial walls around the drill floor, the bottle rack forward of the drill floor, a simplified representation of drilling pipe and risers on the fore and aft decks, and a simplified representation of the derrick. The actual distribution of drilling pipe and risers and other equipment on the decks at the time of the event has not been fully established at this time, and hence a simplified representation was used in this model.

The model also includes a penetration through the drill floor from the moon pool to simulate releases through the actual arrangement of the rotary table. Figure 57 shows the underside of the hull looking port. The moon pool opening in the hull is shown in this figure, along with the extensions of the 2nd and 3rd decks into the moon pool. A closer view of the moon pool is shown in Figure 58. The cylinder shown in this figure is meant to represent the riser. The "break" in the riser which can be seen in this figure is the release point for the "slip joint" release scenario, and the termination of the riser just below the drill floor is the release point for the "riser bore" release scenarios. Comparisons between solid model views from within the moon pool area and photographs of approximately the same area are shown in Figure 59 and Figure 60.

The solid model includes three large openings in the hull between the drill floor and the main deck on the forward wall of the moon pool. There are also two large doors in the BOP House: one on the forward wall and one on the forward end of the port wall. All of these openings would allow gases released in the moon pool to flow onto the main deck of the ship. There are no openings on the starboard or aft sides of the ship. The openings included in the solid model are listed in Table 7. Opening O5_BOP_port was modeled in the "closed" position. Figure 61 shows each opening called out on a plan drawing of the main deck and Figure 62 and Figure 63 provide a comparison of the solid model with photographs of the exterior of the ship. Figure 64 and Figure 65 provide comparisons of the solid model with photographs taken from within the BOP house and the moon pool, respectively.

The monitor locations (monitor points are used within FLACS to record field parameter values, such as fuel concentration) included in the FLACS model are shown in Figure 66 and Figure 67. Those monitor point locations corresponding to the engine room ventilation air intakes on the aft end of the ship are shown separately in Figure 68 and Figure 69. Also shown in Figure 68 are four monitor locations corresponding to supply fans at the port and starboard sides of the forward end of the ship.

The supply and exhaust fans discussed above and listed in Table 4 are included in the FLACS model as discrete momentum sources and sinks. In FLACS nomenclature these are identified as "leaks" and labeled as "suctions" (momentum sinks) or "jets" (momentum sources). The ventilation system "leaks" included in the FLACS model are shown in Figure 70 (from above) and Figure 71 (from aft). Figure 72 and Figure 73 show the gas release point for the riser bore, Figure 74 and Figure 75 show the gas release point for the mud separator vent, Figure 76 and

Figure 77 show that gas release point for the mud-gas rupture disk outlet, Figure 78 and Figure 79 show the gas release point for the slip joint, Figure 80 and Figure 81 show the gas release point for the mud pit room exhaust fans, and Figure 82 and Figure 83 show the gas release point for the vacuum breaker vent.

Table 7. Moon Pool and BOP House Openings and Corresponding Dimensions

Side	Section (Structure)	Opening	Dimension (Width x Height)
Forward	Moon Pool	O1_MP_stbd	7 m x 4 m
		O2_MP_mid	4.5 m x 4 m
		O3_MP_port	4.5 m x 4 m
	BOP	O4_BOP_fwd	2.4 m x 10 m
Port		O5_BOP_port	5 m x 10 m
Starboard	None		
Aft	None		

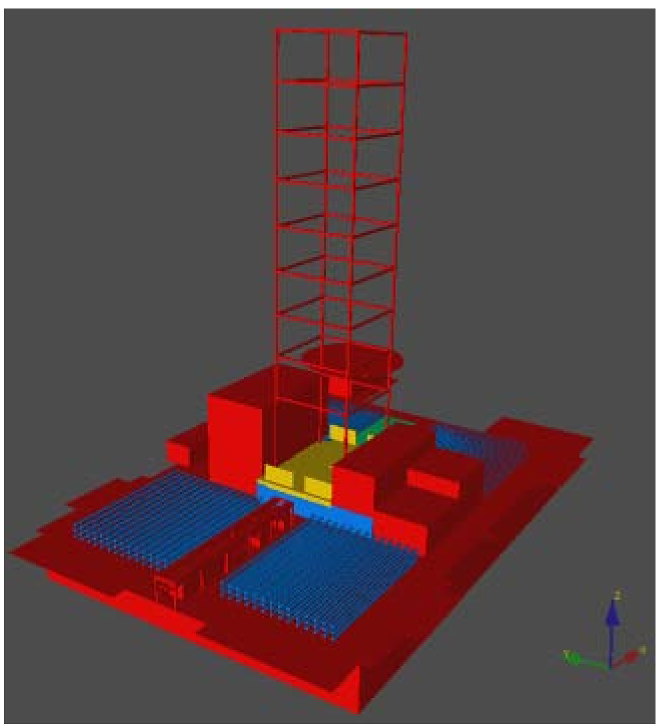


Figure 54. Solid Model, View from Starboard Aft to Port Forward

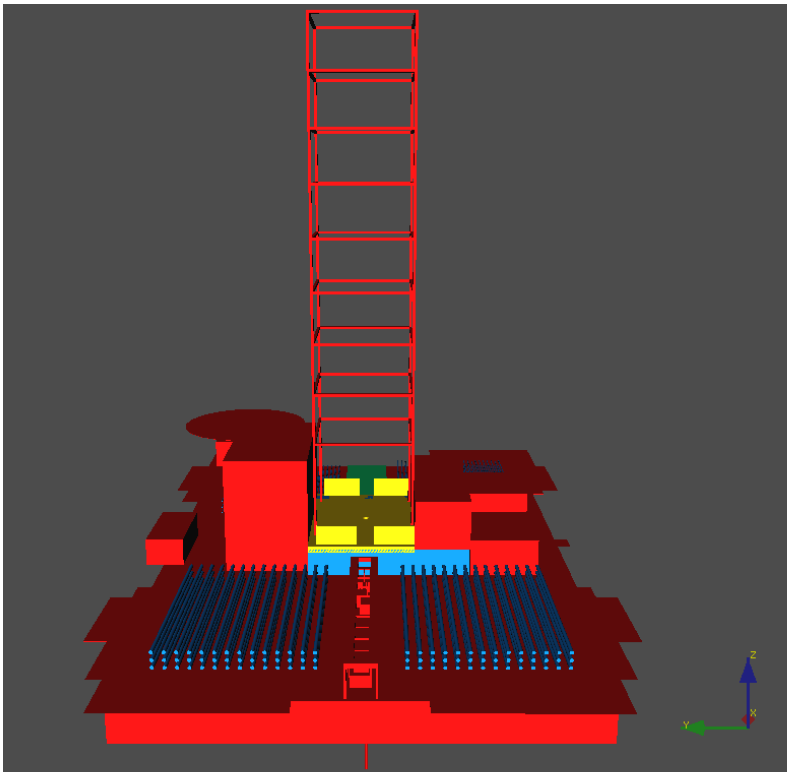


Figure 55. Solid Model, View from Aft

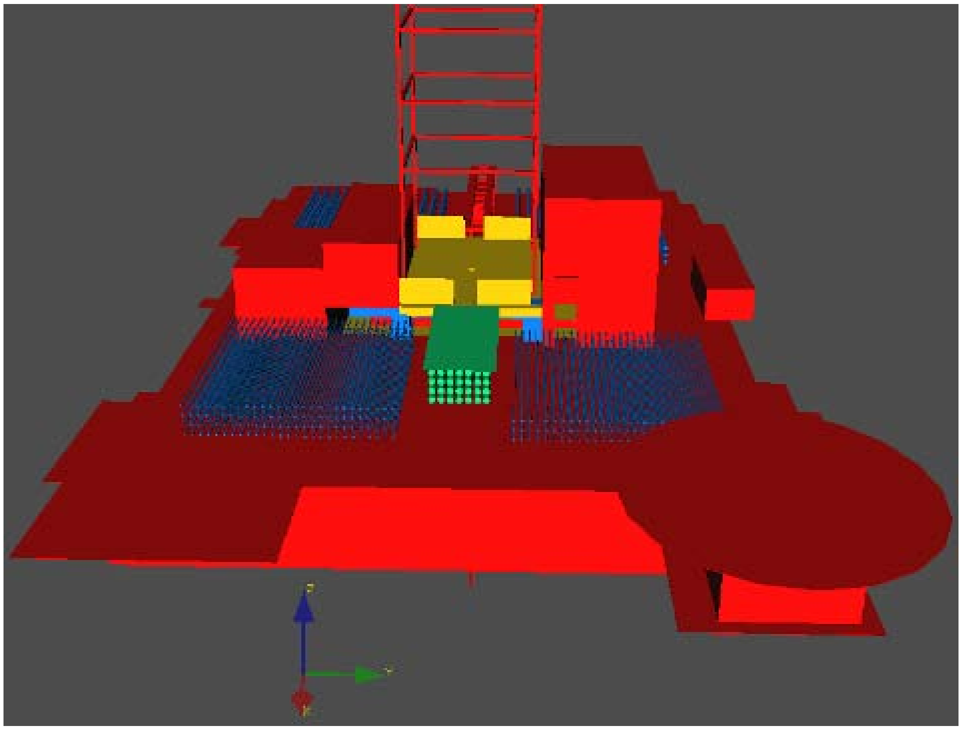


Figure 56. Solid Model, View from Forward

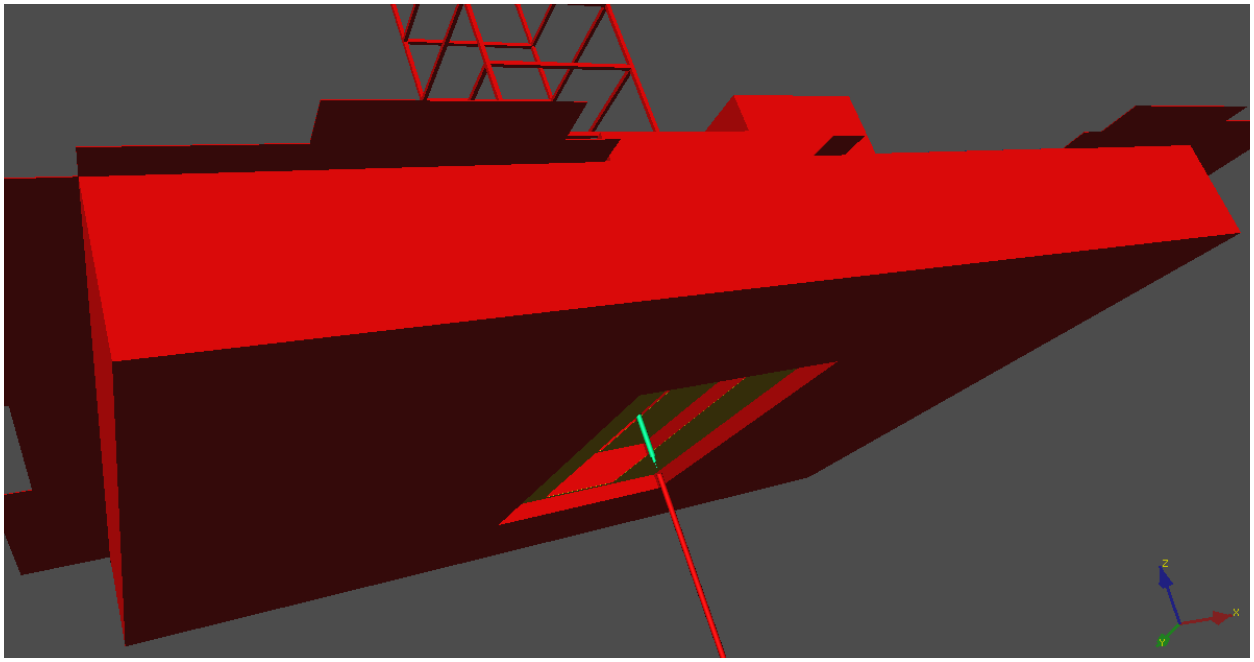


Figure 57. Solid Model, View from Bottom of Hull (looking port)

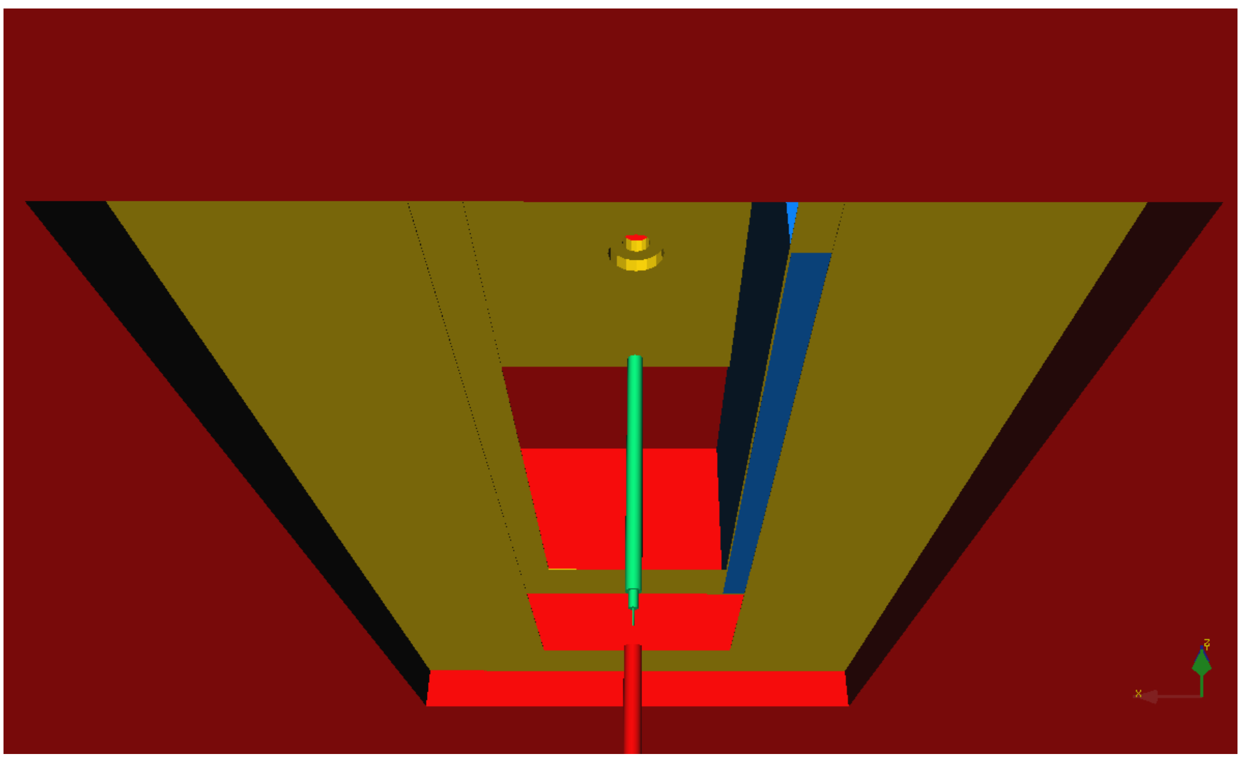


Figure 58. Solid Model, View from Bottom of Moon Pool (looking starboard)

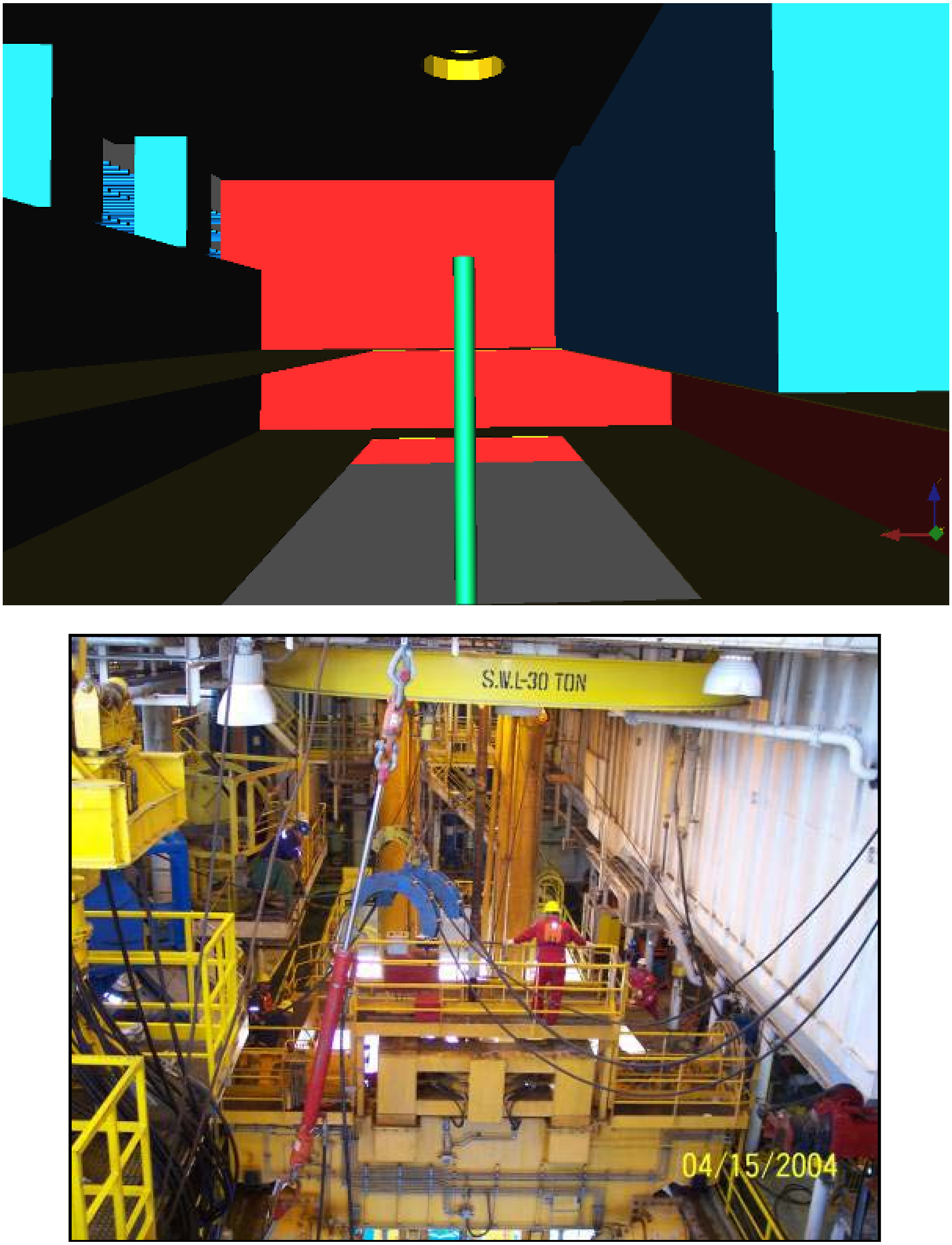


Figure 59. Comparison of Solid Model Moon Pool (looking starboard) with Photograph

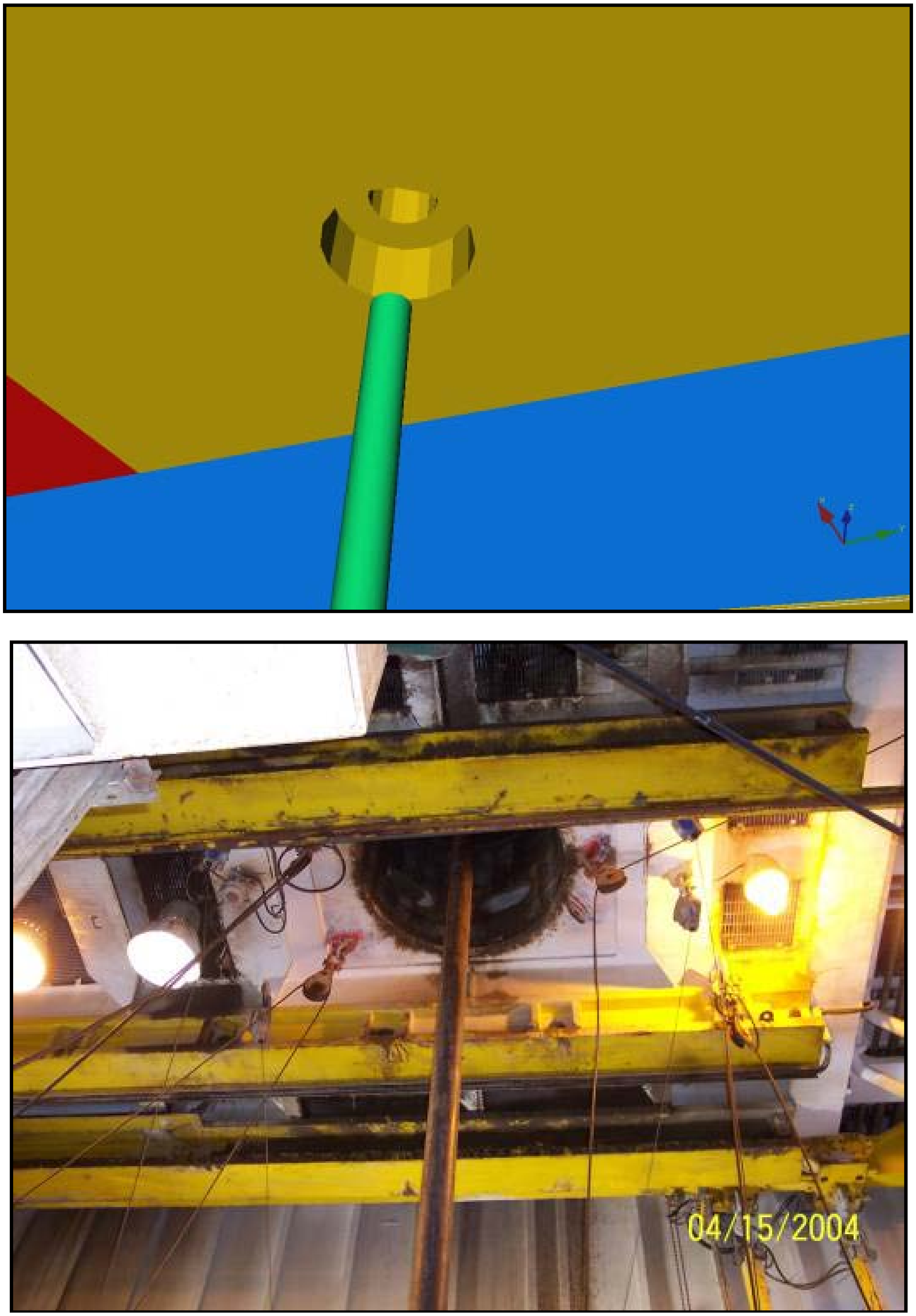


Figure 60. Comparison of Solid Model Moon Pool (looking up towards drill floor) with Photograph

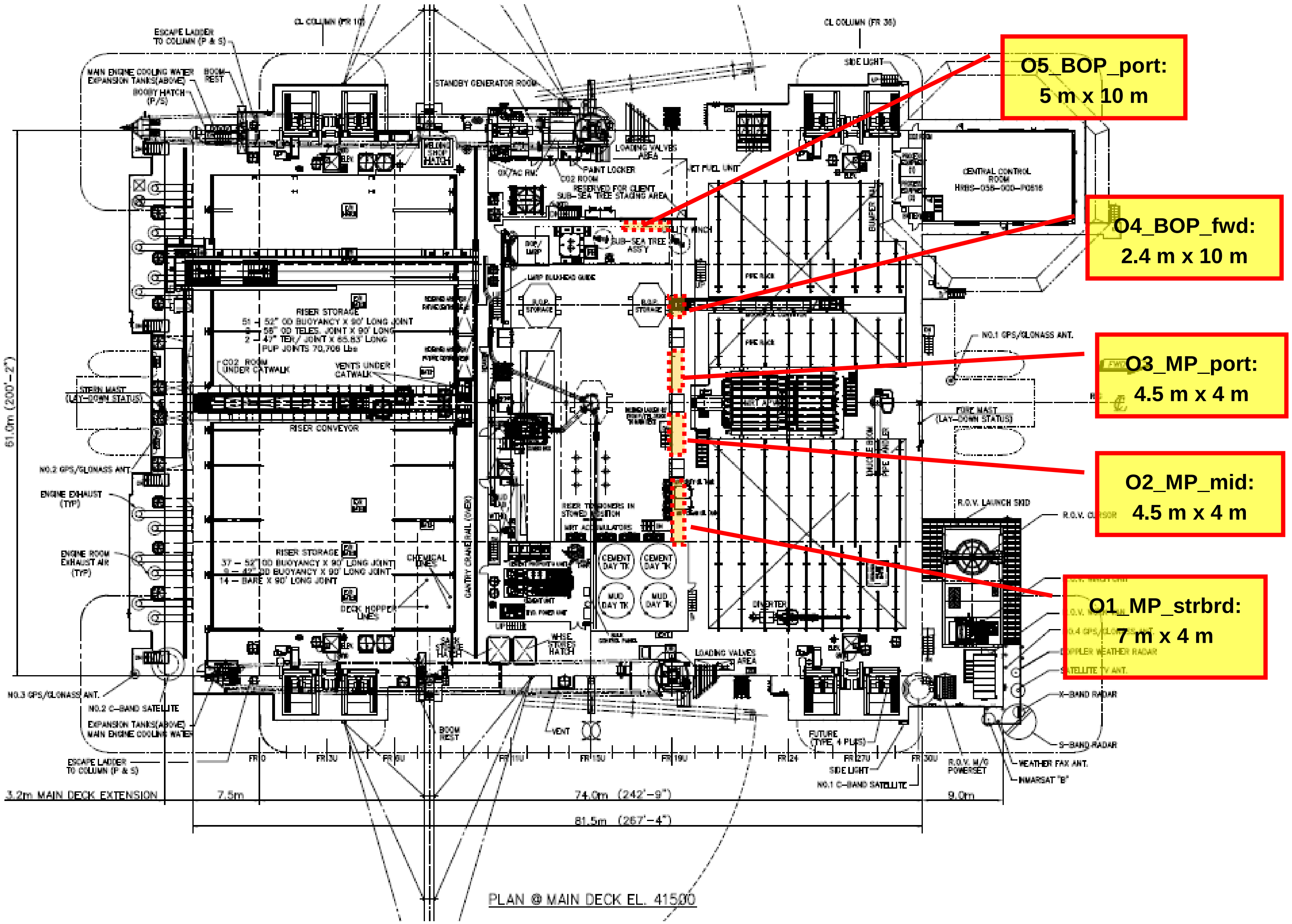
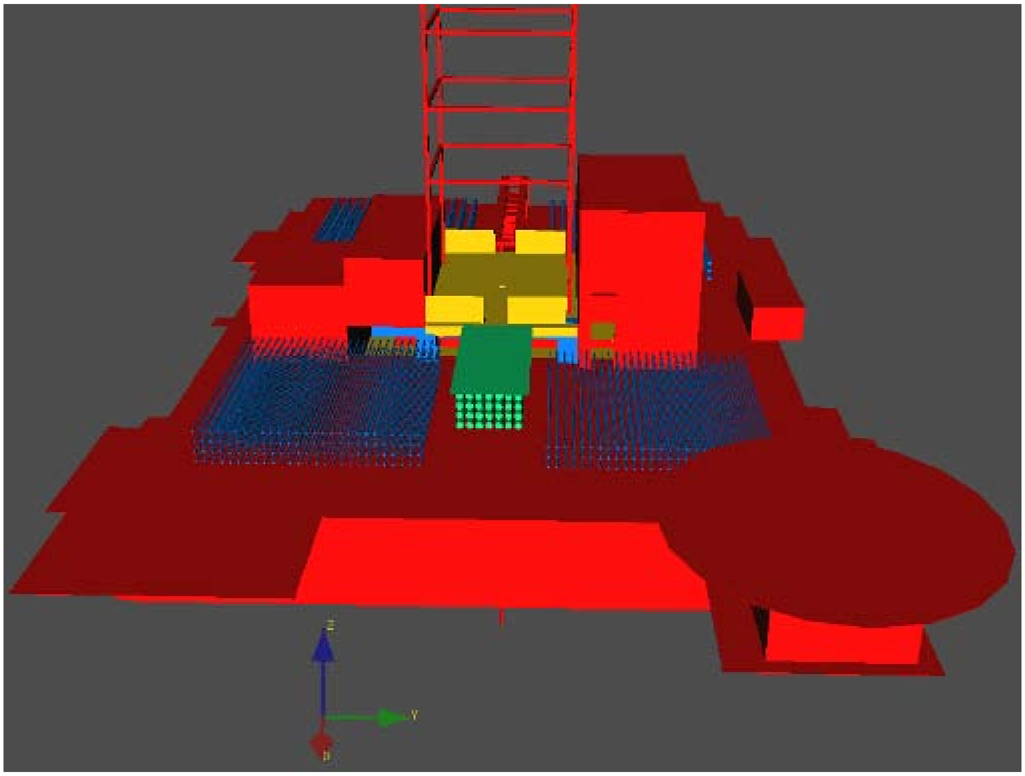


Figure 61. Openings between the Main Deck and Drill Floor (HRBS-058-000-P0607, rev.5)



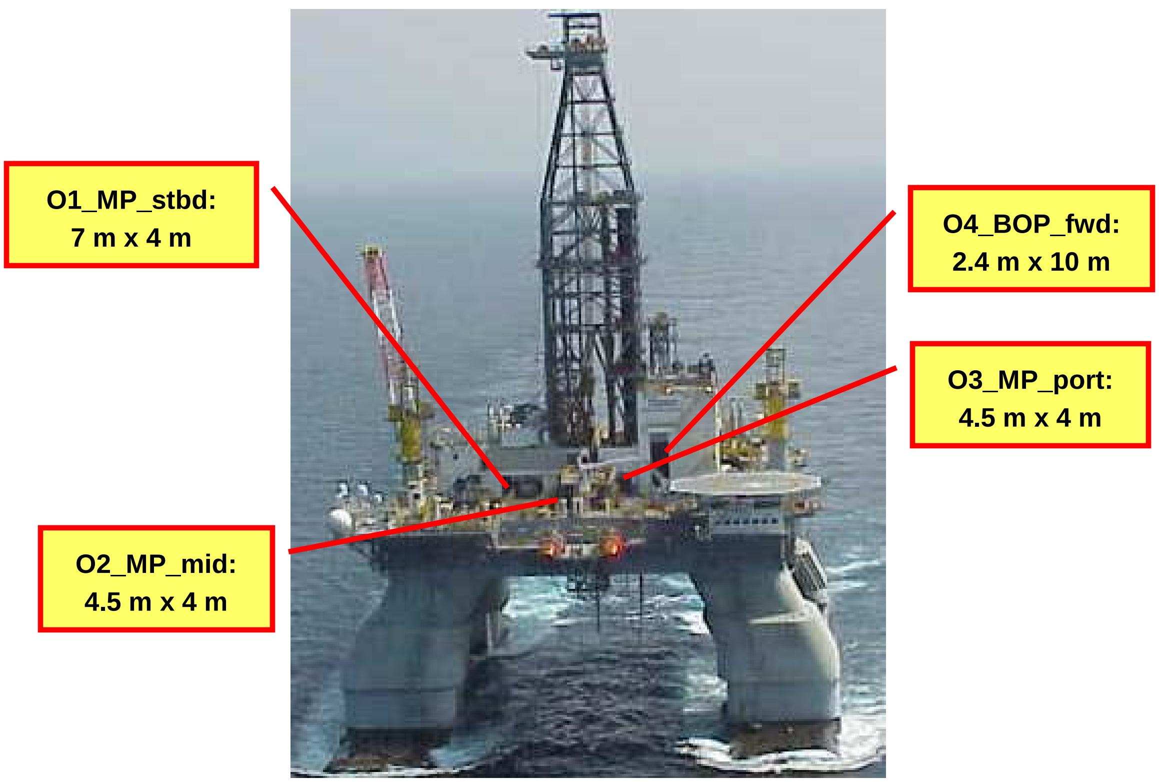


Figure 62. Comparison of Forward Openings in Solid Model with Photograph

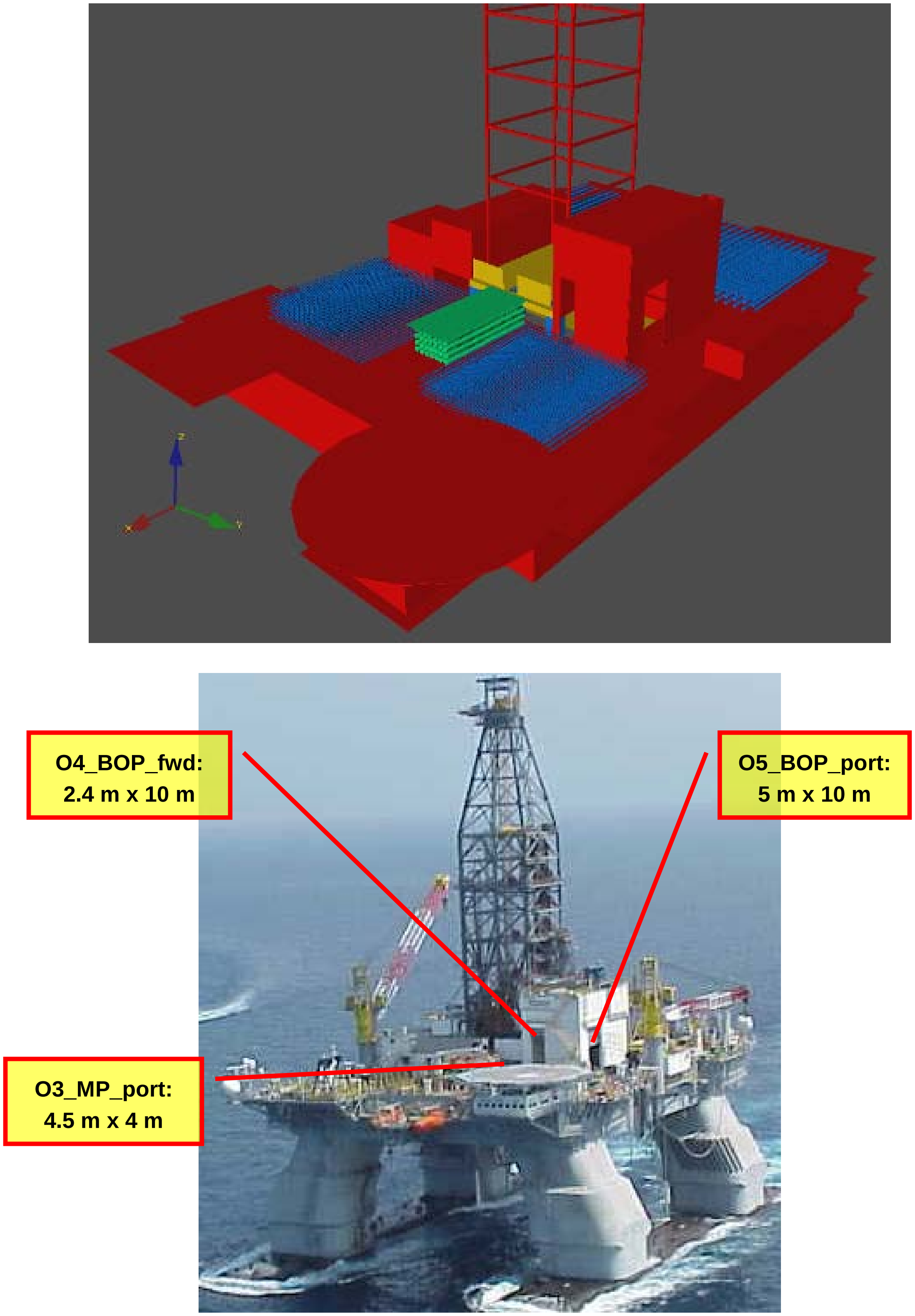
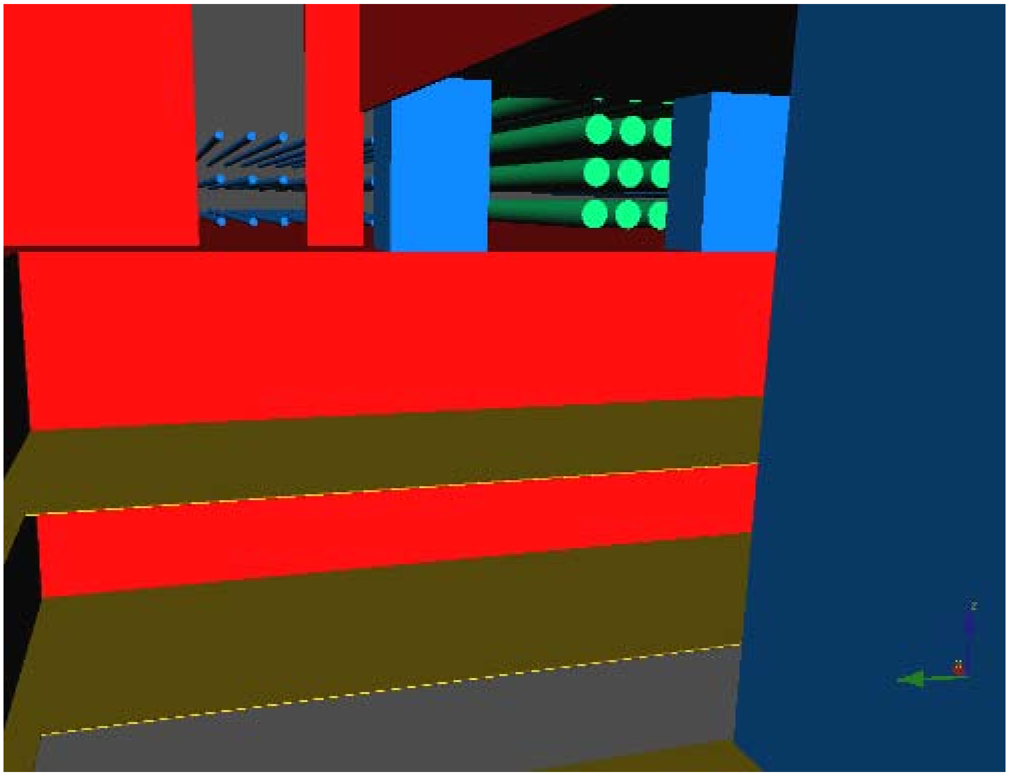


Figure 63. Comparison of Forward and Port Openings in Solid Model with Photograph



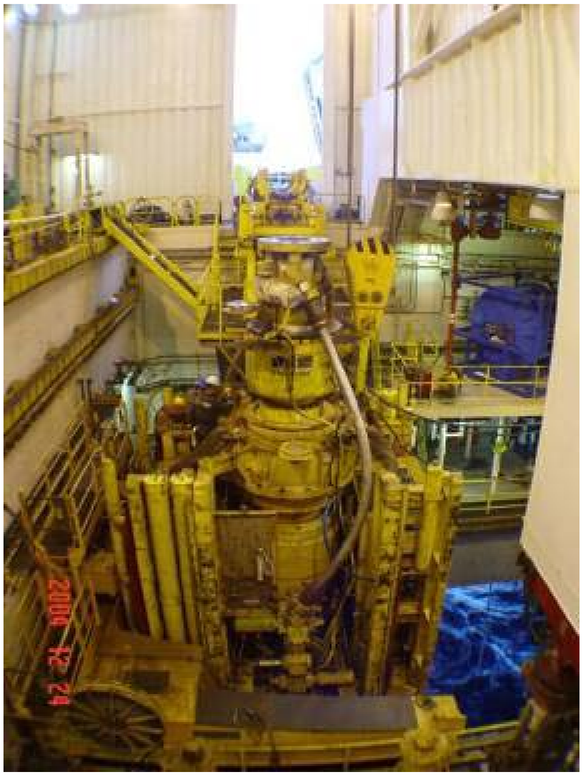


Figure 64. Comparison of Solid Model BOP House with Photograph (looking forward)

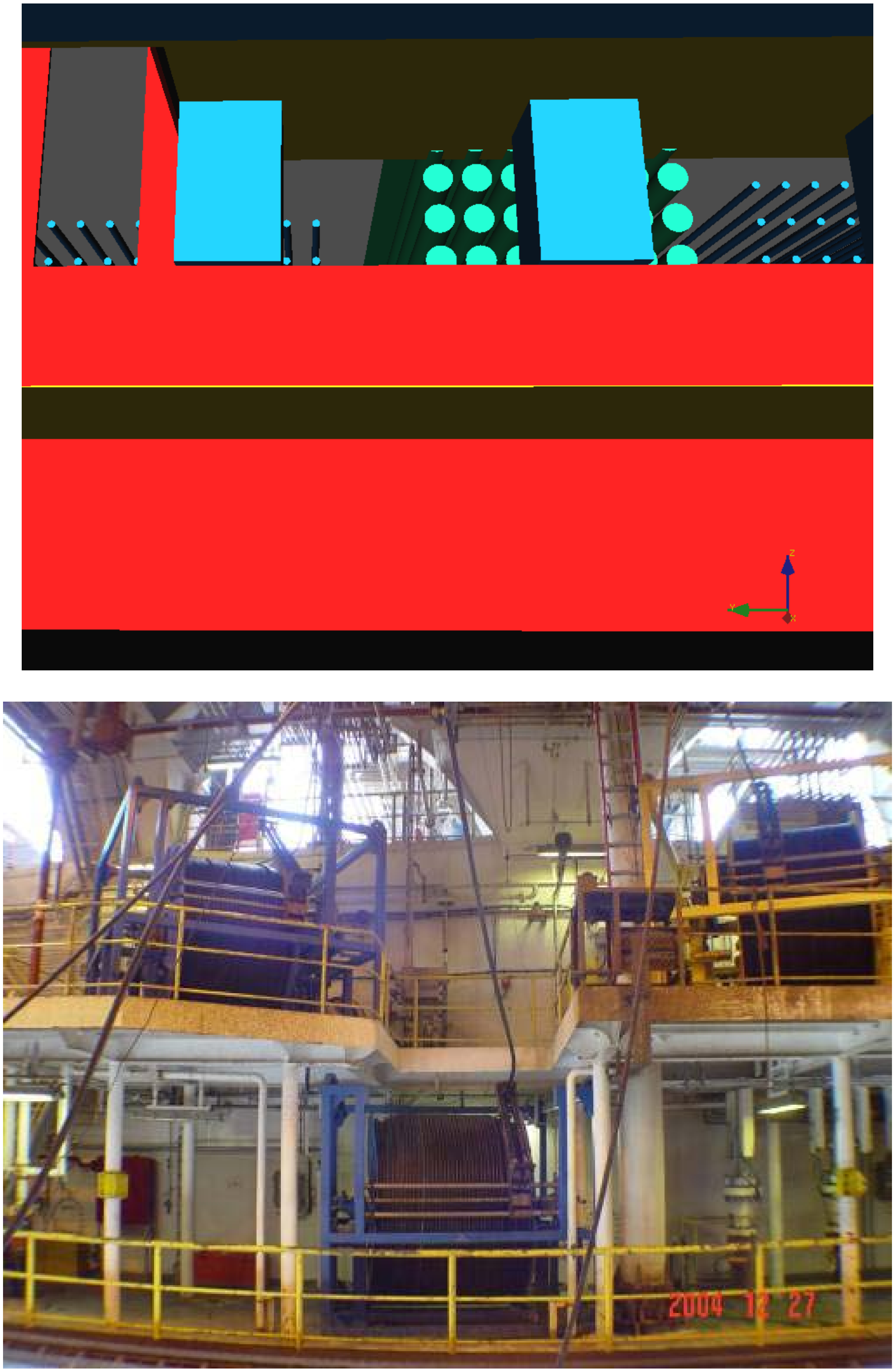


Figure 65. Comparison of Forward Openings in Solid Model Moon Pool with Photograph (looking forward)

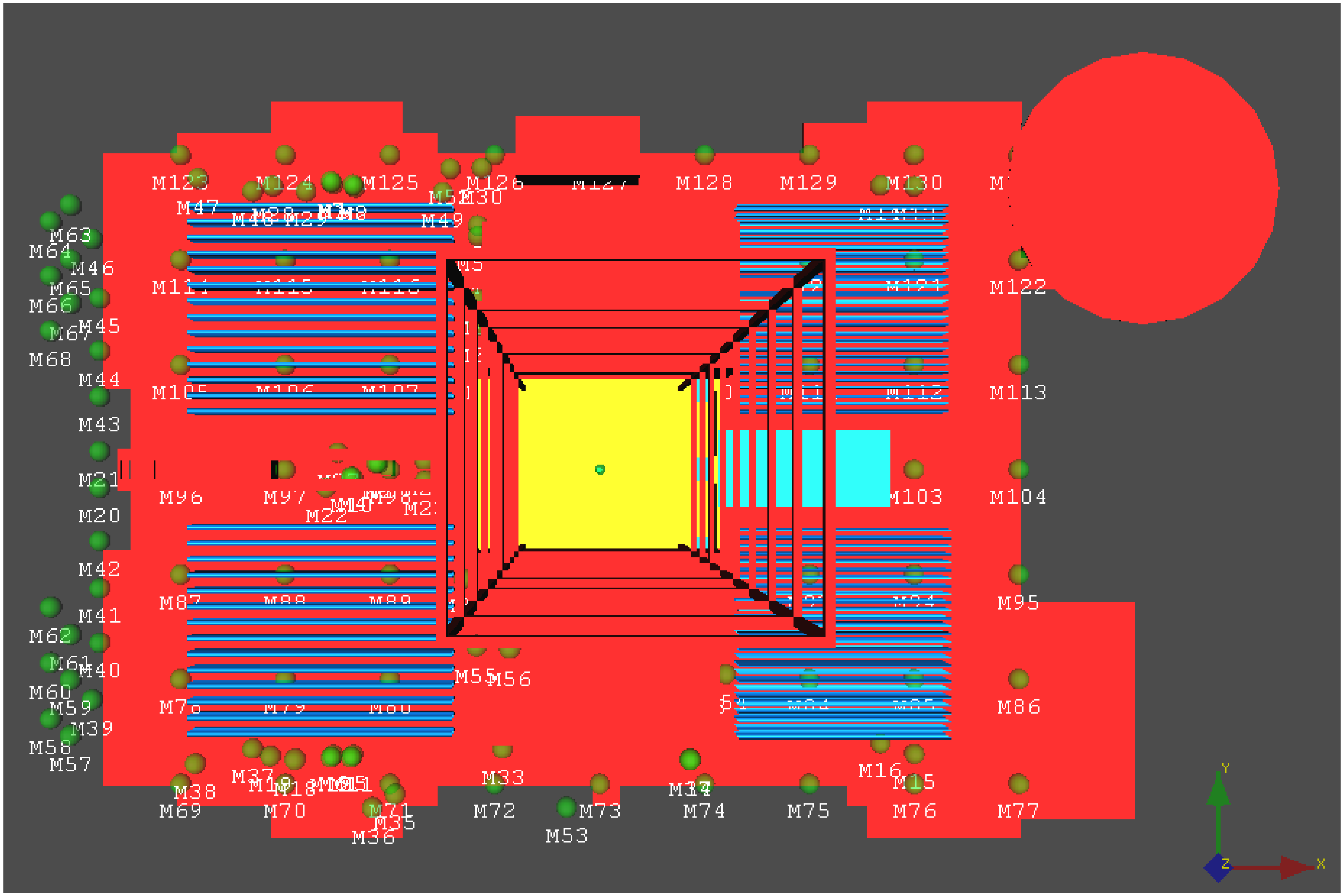


Figure 66. Solid Model, View from Above Derrick with Monitor Locations

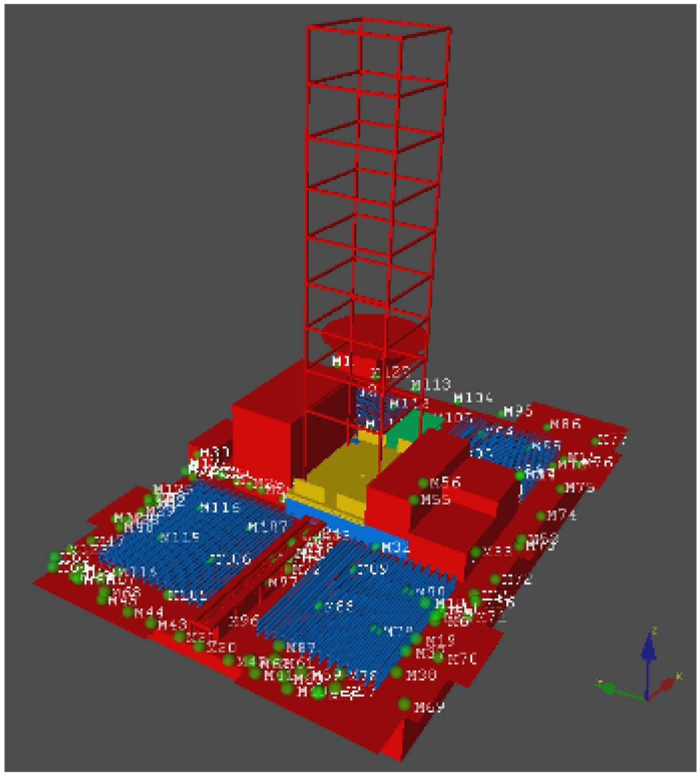


Figure 67. Solid Model, View from Starboard Aft with Monitor Locations

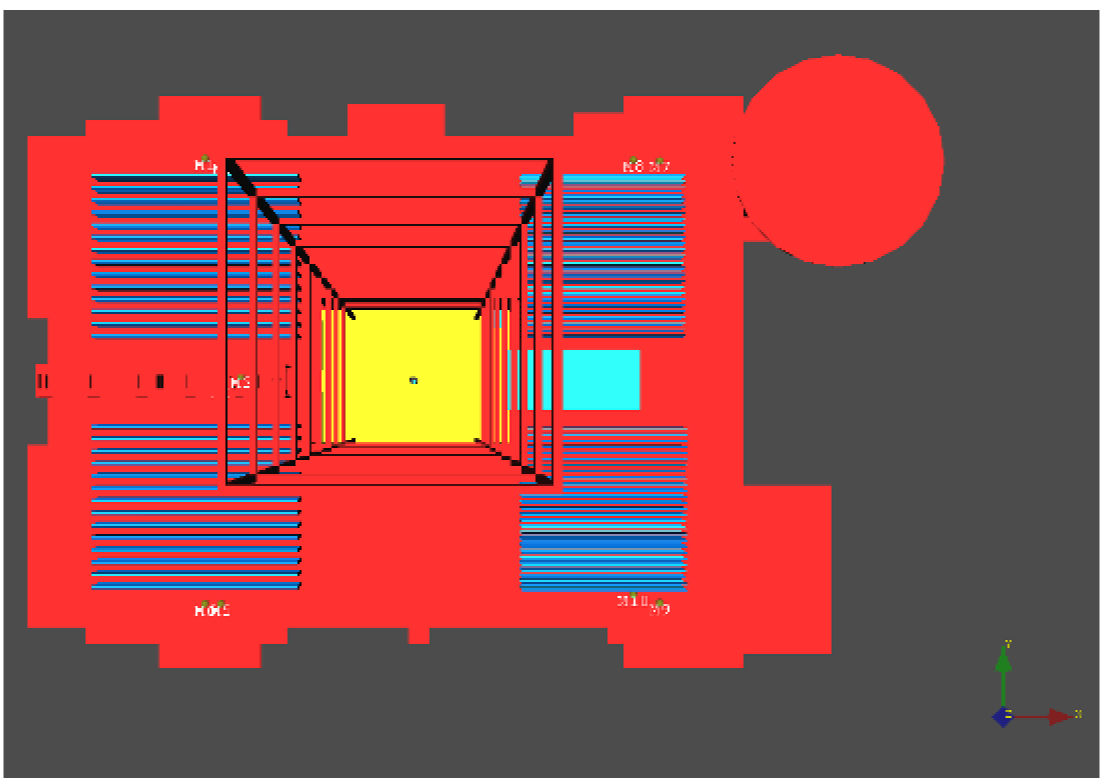


Figure 68. Solid Model, View from Above Derrick with Selected Monitor Locations

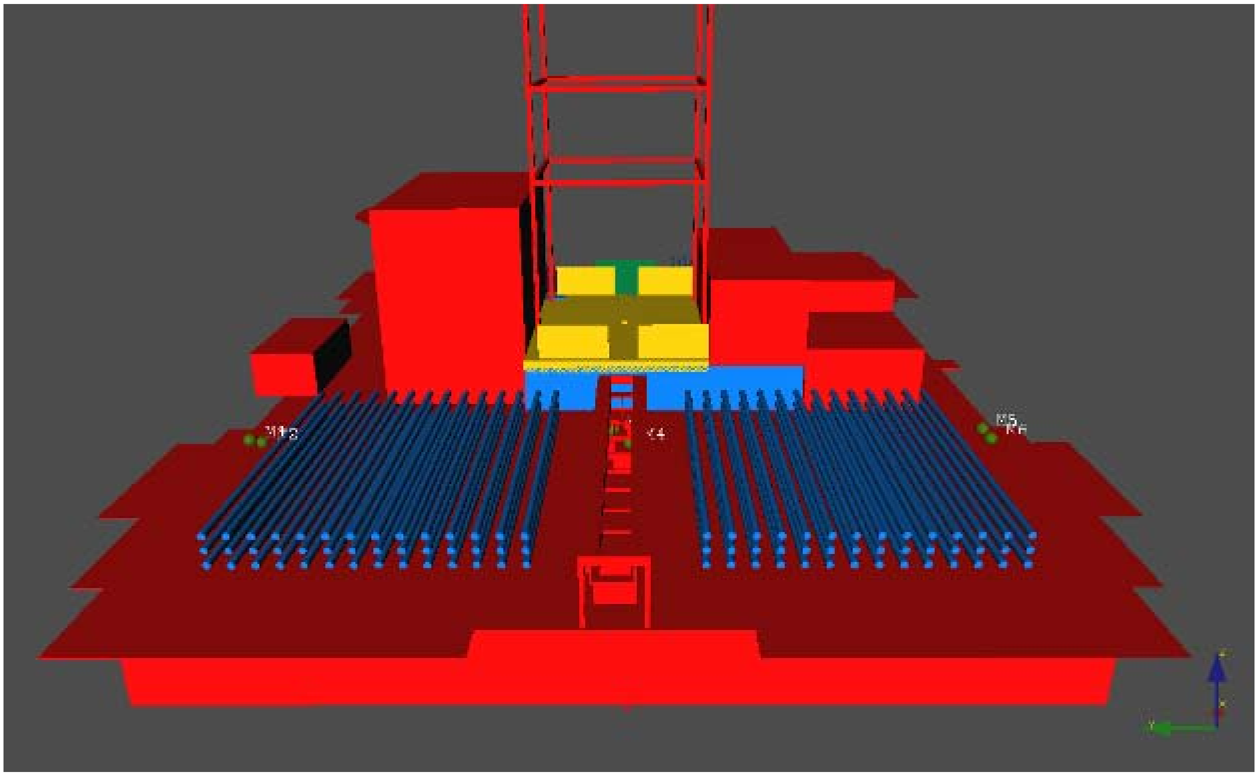


Figure 69. Solid Model, View from Aft with Selected Monitor Locations

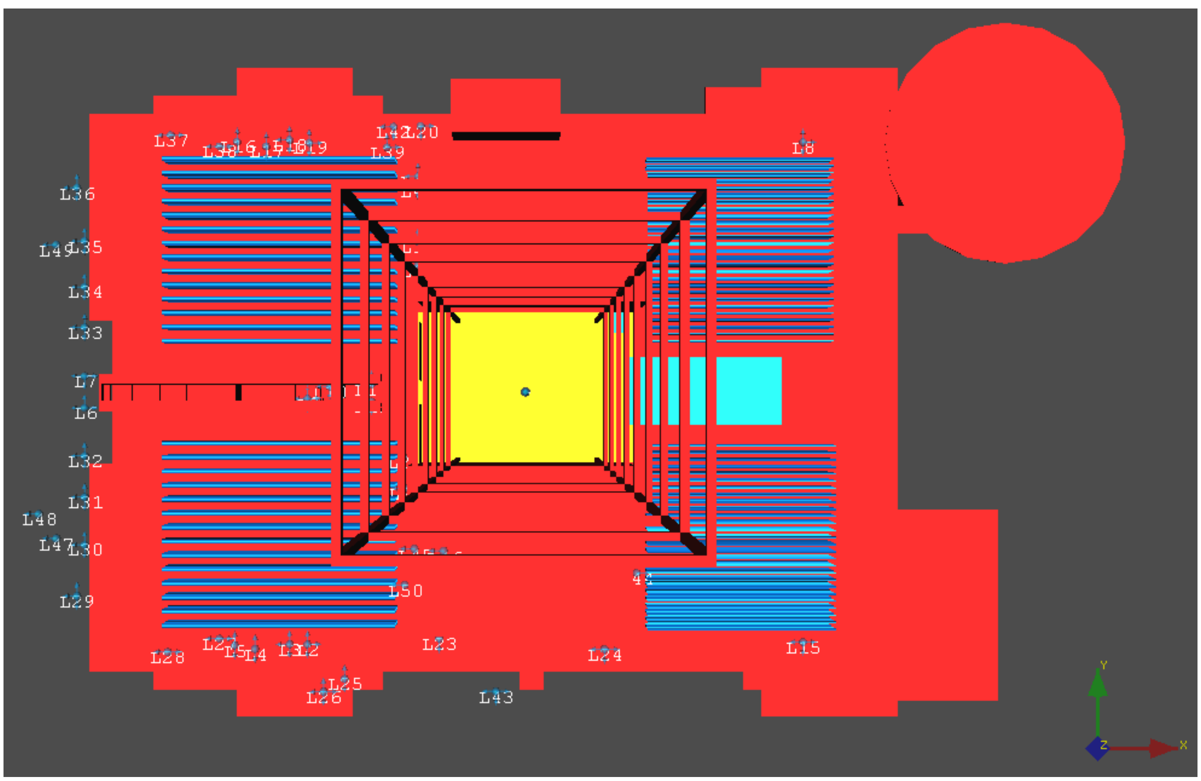


Figure 70. Solid Model, View from Above Derrick with Ventilation System

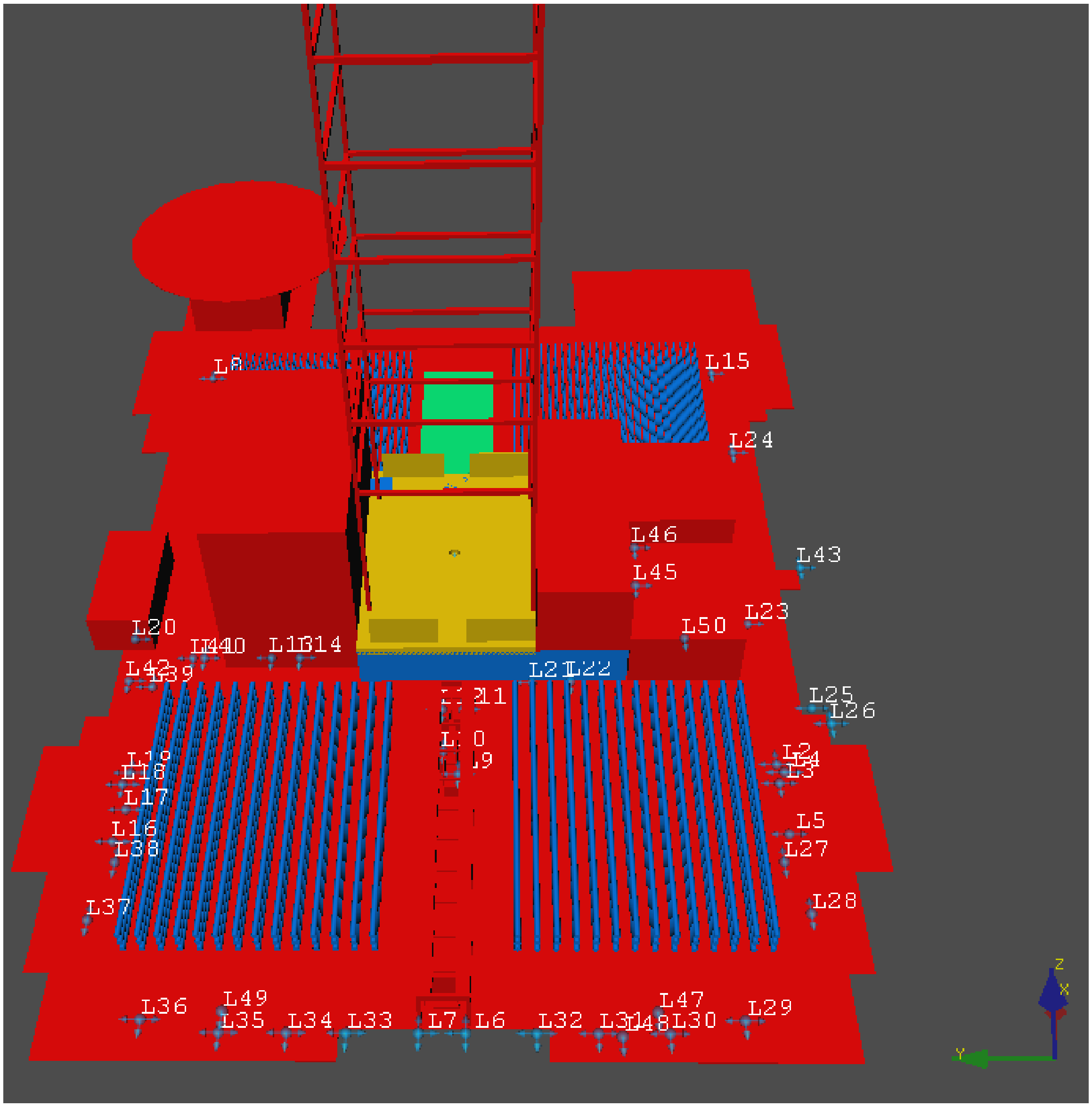


Figure 71. Solid Model, Viewed from Aft with Ventilation System

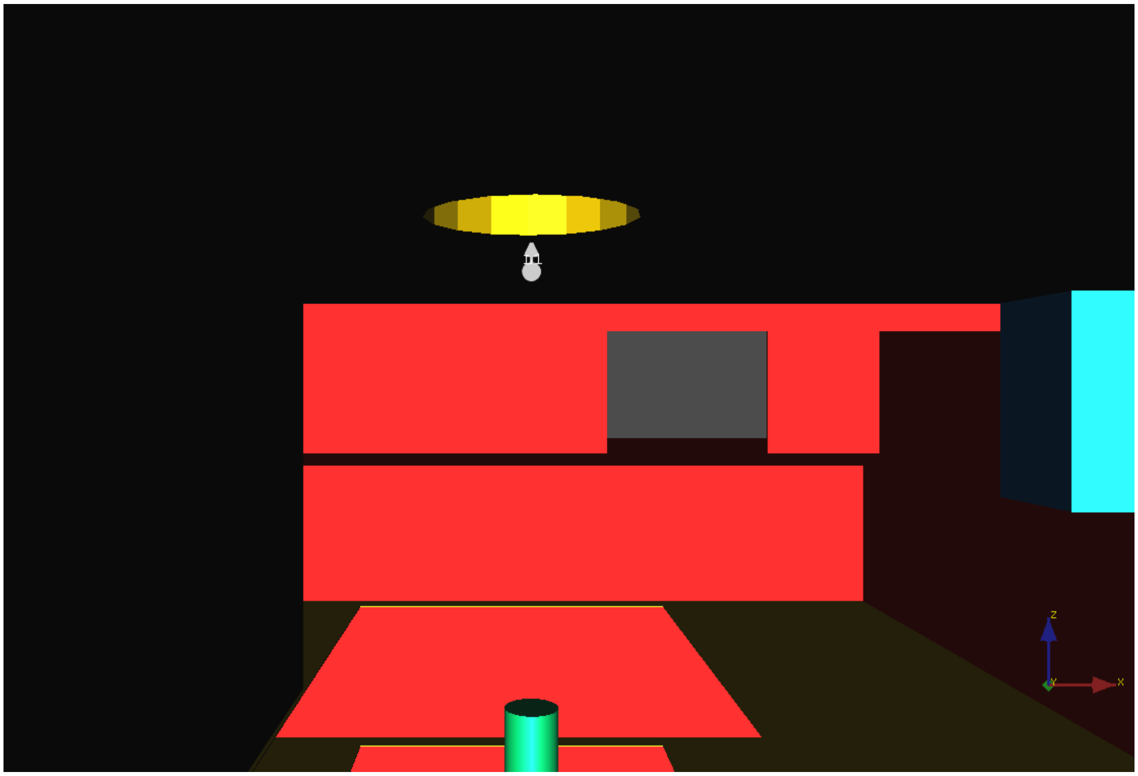


Figure 72. Solid Model , Riser Bore Release Point (looking port)

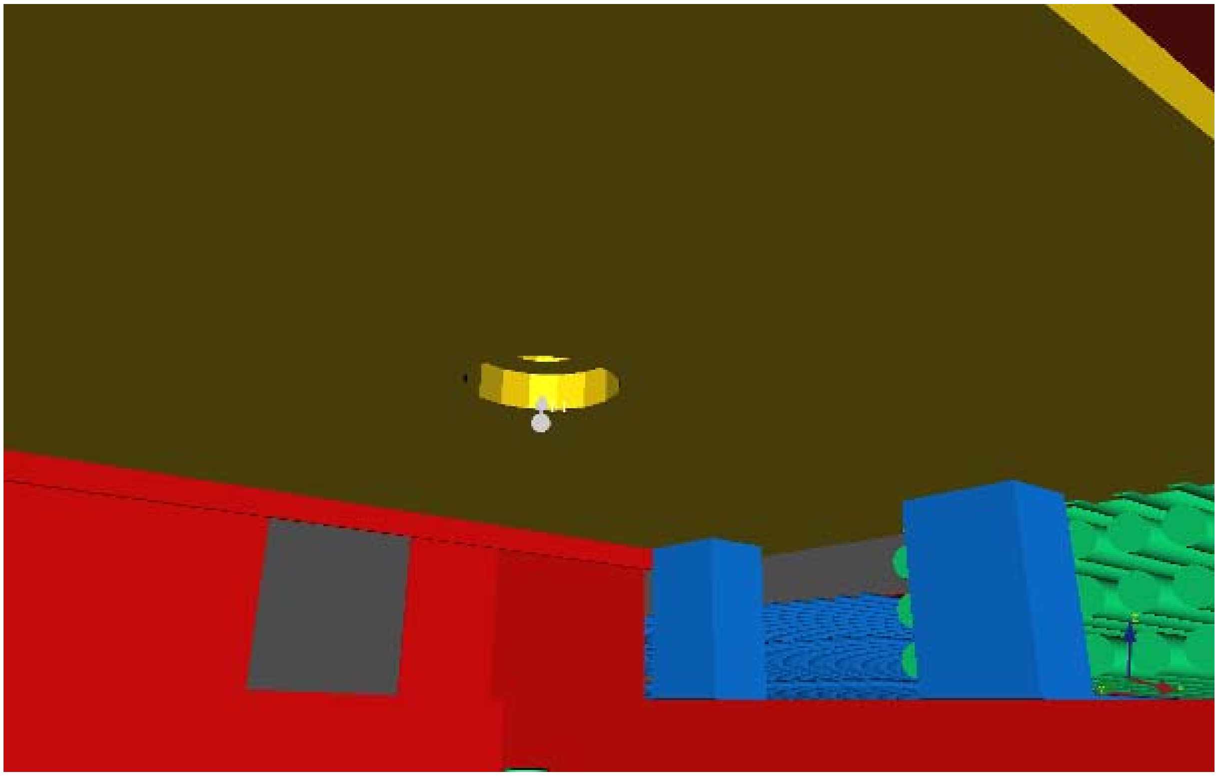


Figure 73. Solid Model, Riser Bore Release Point (looking forward port)

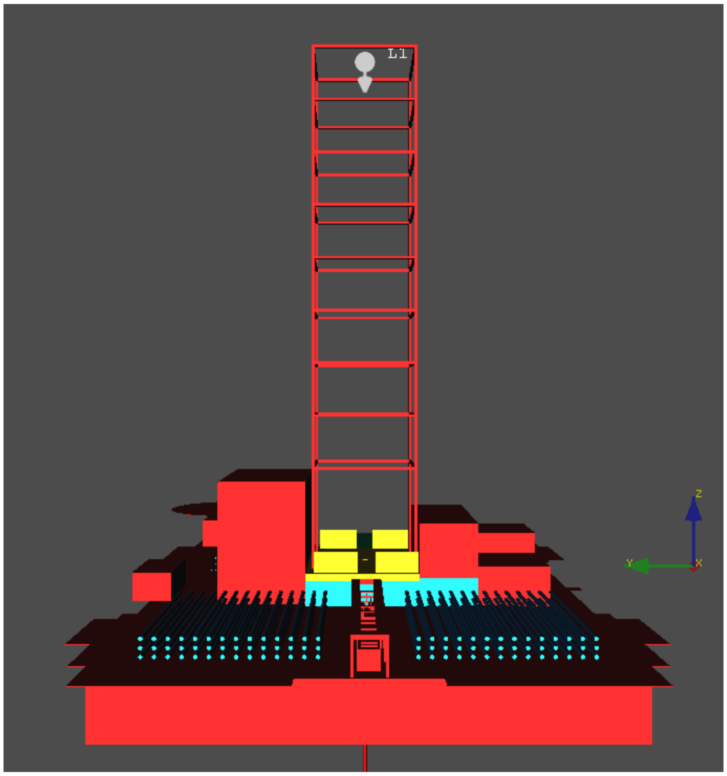


Figure 74. Solid Model, Mud-Gas Separator Release Point (aft view)

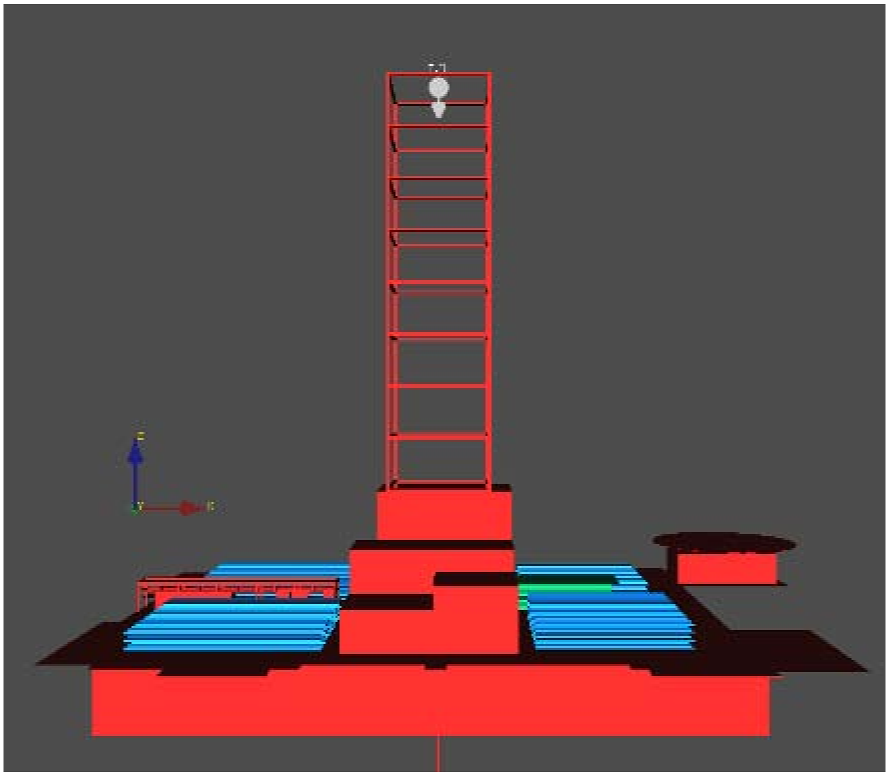


Figure 75. Solid Model, Mud-Gas Separator Release Point (starboard view)

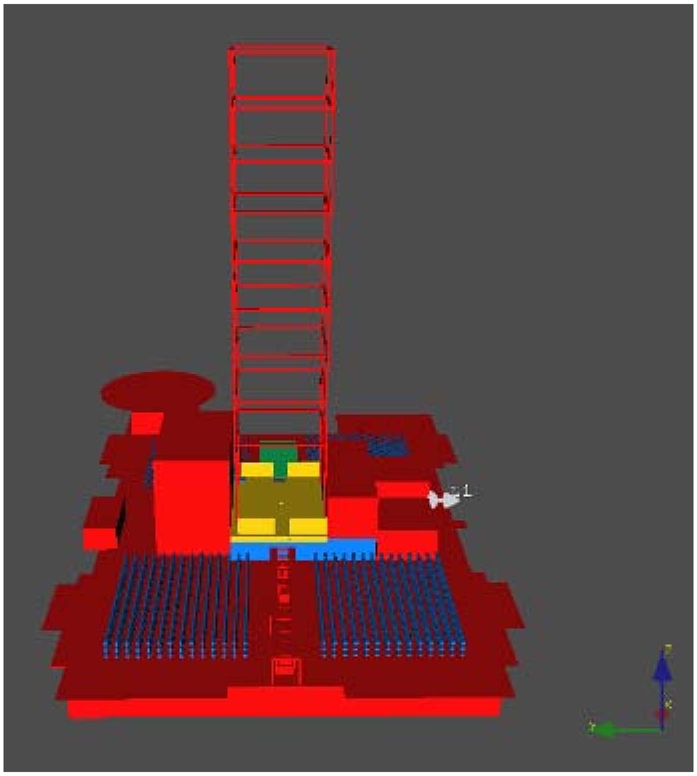


Figure 76. Solid Model, Mud-Gas Rupture Disk Outlet Release Point (aft and above view)

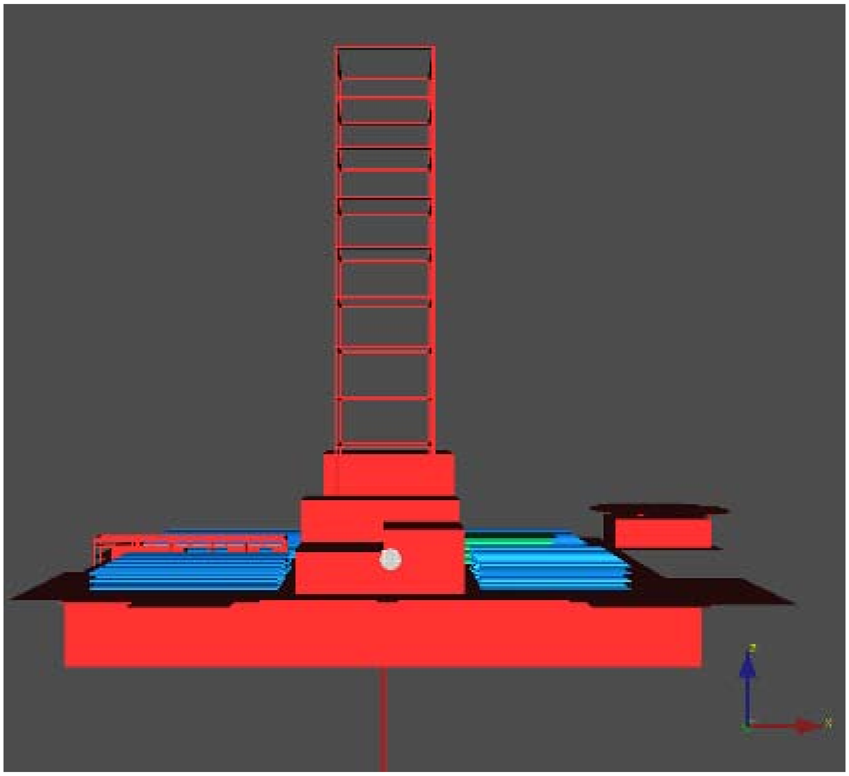


Figure 77. Solid Model, Mud-Gas Rupture Disk Outlet Release Point

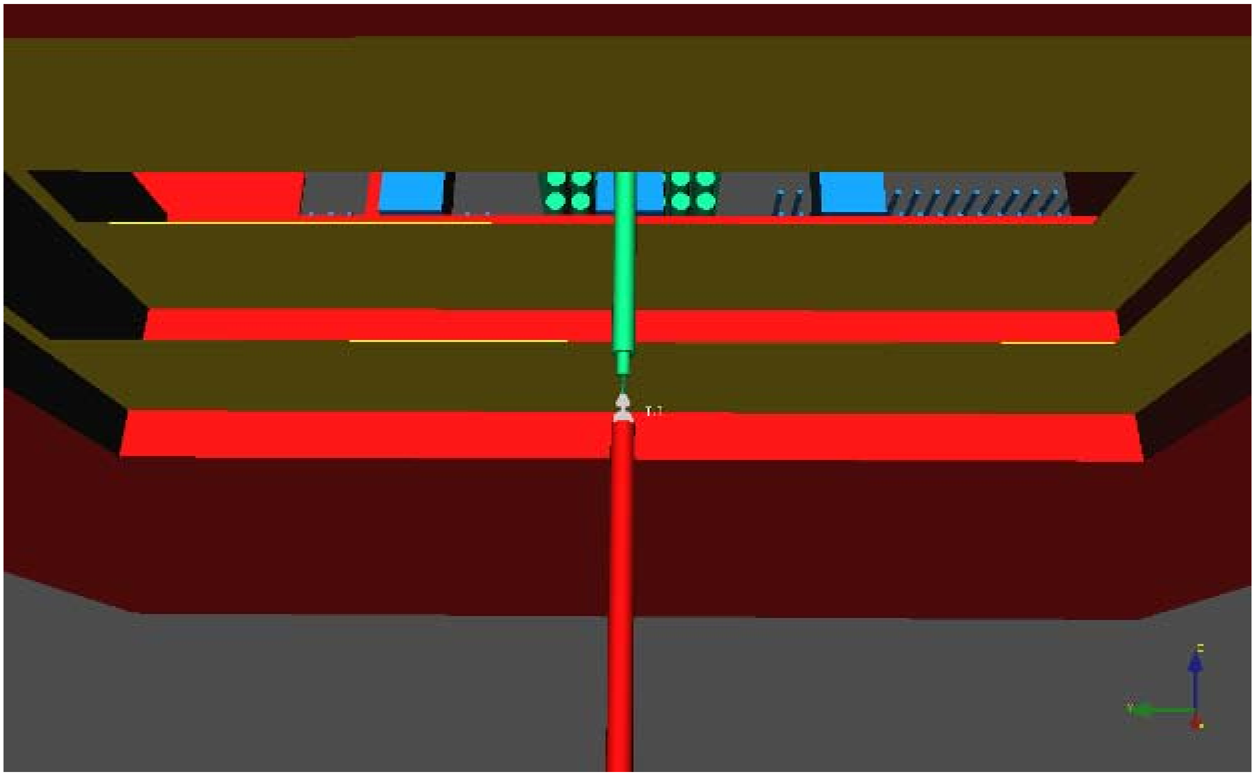


Figure 78. Solid Model, Slip Joint Release Point (looking forward)

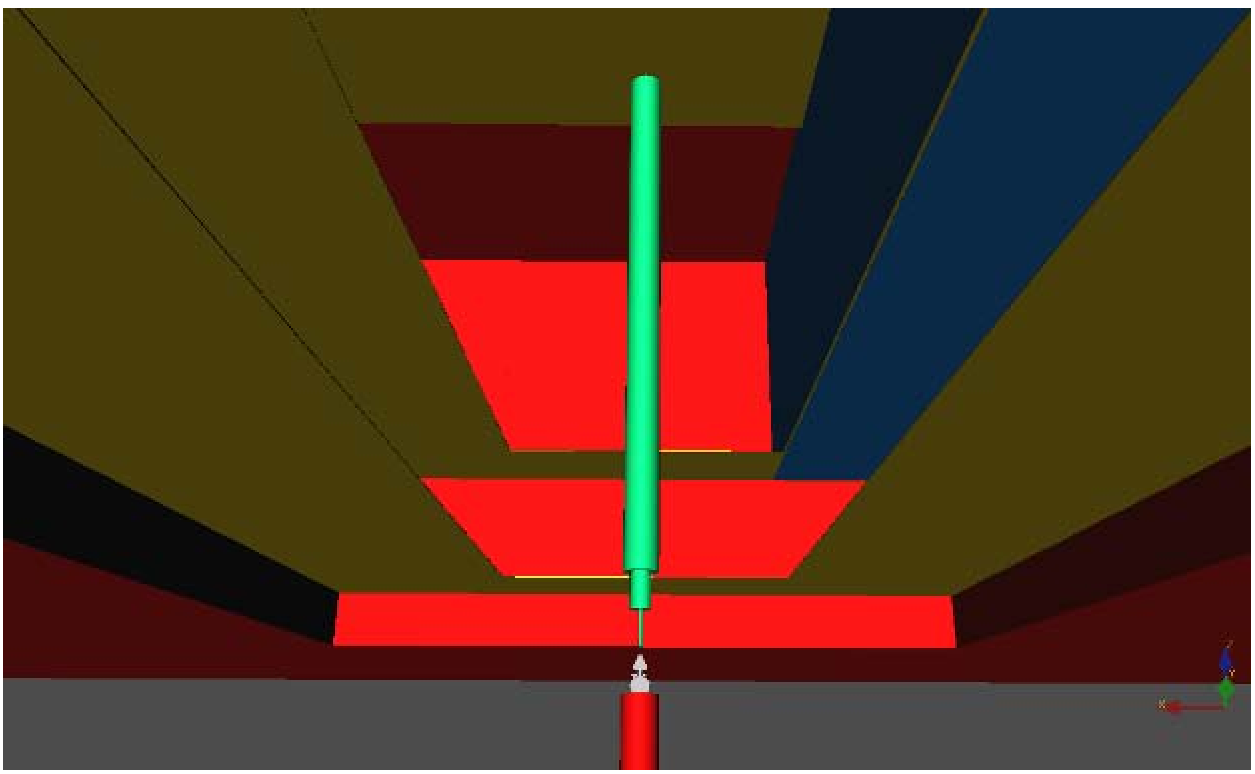


Figure 79. Solid Model, Slip Joint Release Point (looking starboard)

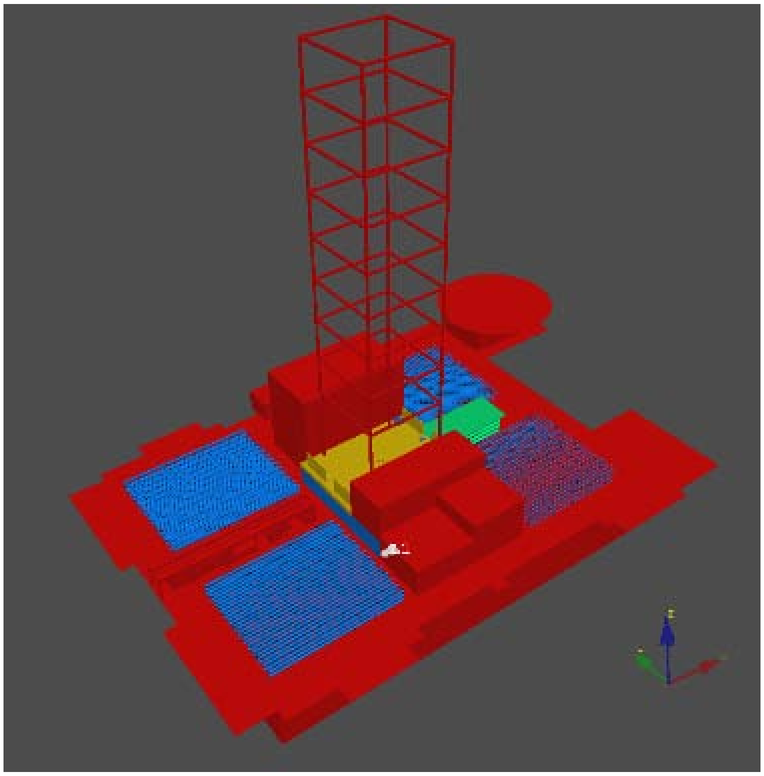


Figure 80. Solid Model, Mud Room Exhaust Release Point (starboard and above view)

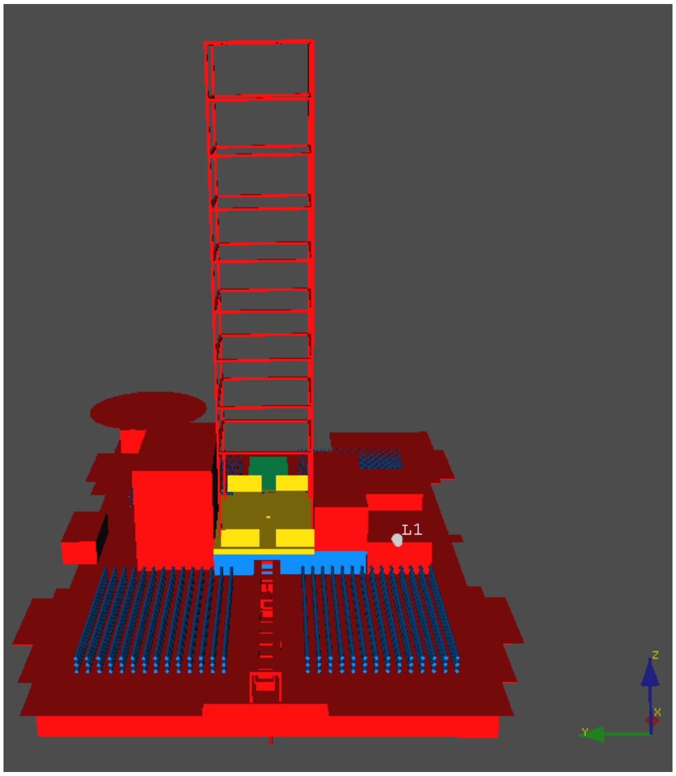


Figure 81. Solid Model, Mud Room Exhaust Release Point (aft and above view)

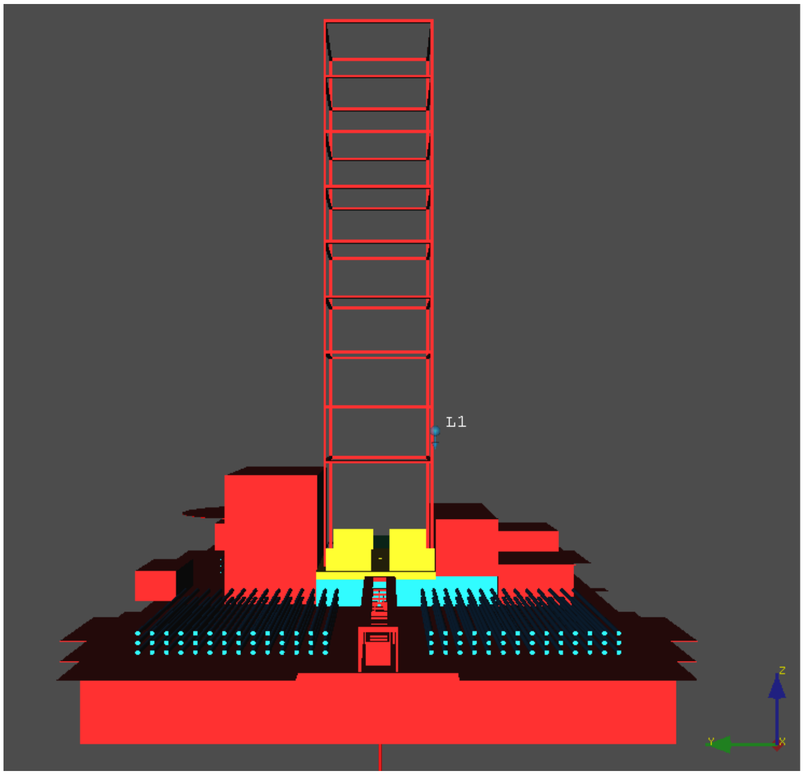


Figure 82. Solid Model, Vacuum Breaker Vent Release Point (aft view)

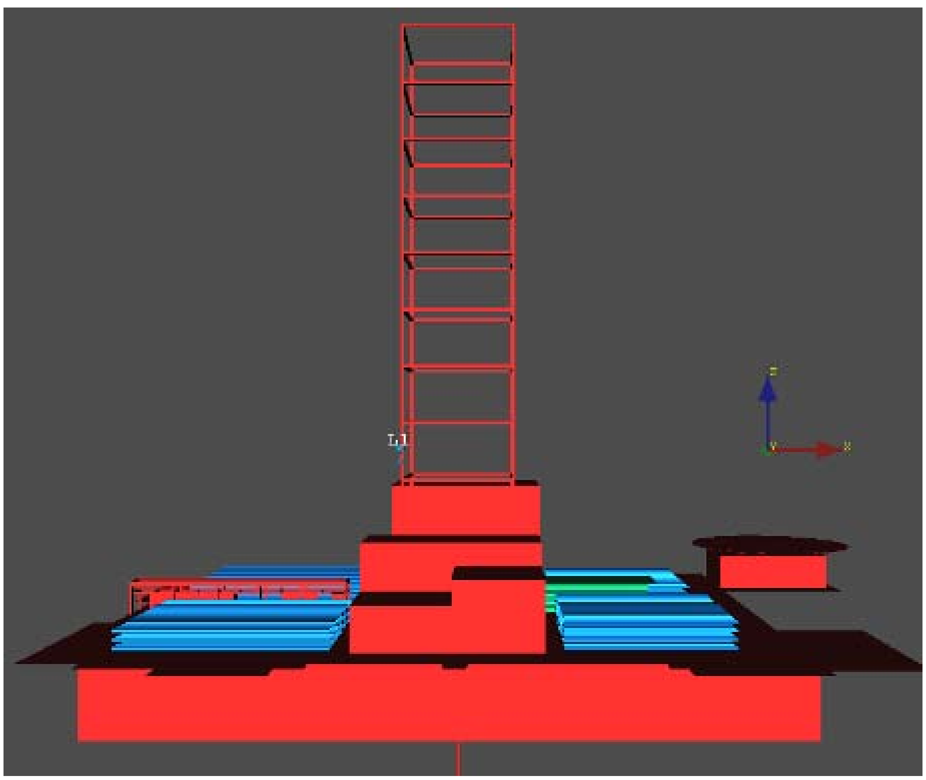


Figure 83. Solid Model, Vacuum Breaker Vent Release Point (starboard view)

6 RESULTS AND DISCUSSION

6.1 Scenario A

The Scenario A release described previously in Section 4.4.7 was evaluated with the wind from port (to starboard) at 2 m/s. The simulation was first run for 60 seconds without gas release to establish a steady-state flow field due to the wind. The ventilation sources and sinks listed in Table 4 and shown in Figure 70 and Figure 71 were assumed to be in operation for the duration of the simulation, including this 60 second "start-up" period. A vector plot representing the wind field immediately prior to the gas release in the xy-plane located three meters above the main deck (representative of the engine room supply air louvers), is shown in Figure 84. Note that the supply and exhaust fans as well as the buildings and obstructions on the main deck influence the wind field significantly. In particular, large recirculation zones are formed behind the control building under the helipad, at the forward side of the drill floor, and aft of the drill floor at mid-ship due to the combination of the ship's geometry and the location of the supply and exhaust ventilation. Also note that air flows from within the moon pool outward through the doors in the BOP house and through the openings on the forward side of the moon pool.

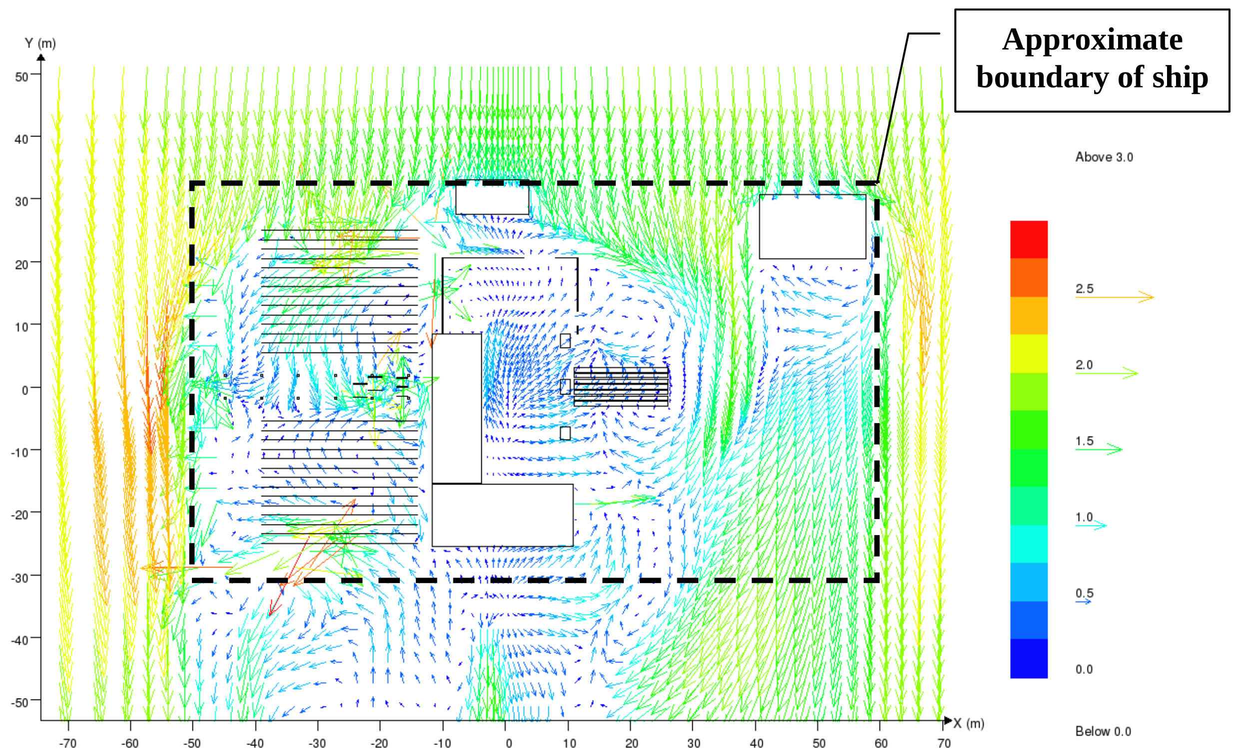


Figure 84. Wind Field 3 m. above the Main Deck Immediately Prior to Gas Release

In the simulation, the release of flammable gas began at 60 seconds and followed the flow rate profile shown in Figure 52. This figure has been duplicated below on a mass flow rate basis as Figure 85 for the convenience of the reader. The total duration of the release was 510 seconds (8.5 minutes). As noted previously, a total of 1.2 MMscf of gas was released. The simulation was run through another 60 seconds beyond the termination of flammable gas release.

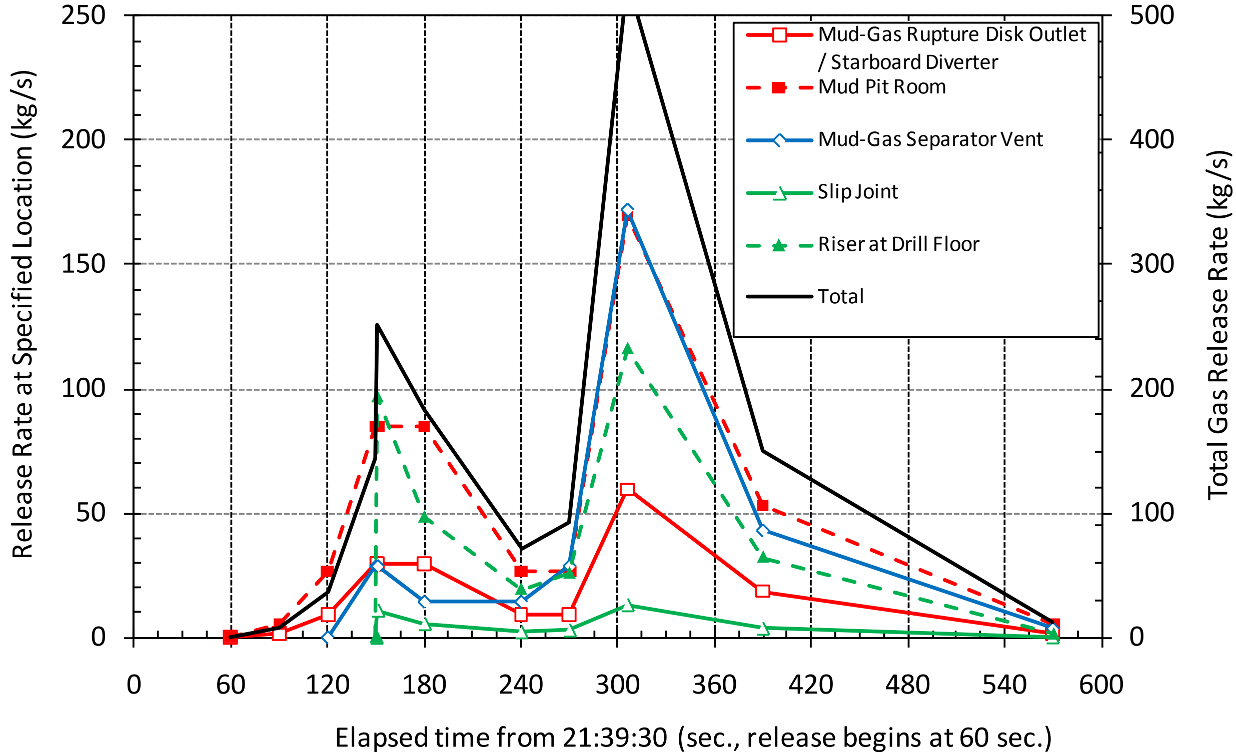


Figure 85. Scenario A Gas Flow Rate (kg/s) as a Function of Time from Each Release Point

The flammable gas cloud developed due to the release profile shown in Figure 85 is shown at 1, 100, 120, 140, 300, and 360 seconds after the release (i.e., at 61, 160, 180, 200, 360, and 420 seconds) in Figure 86 through Figure 91. These figures provide a cut plane through the well center along the starboard-port plane looking aft and a cut plane through the well center along the forward-aft plane looking aft-starboard. The upper and lower end of the contours shown in the figure correspond to the fuel mixture's lower flammability limit (LFL) and upper flammability limit (UFL) for the prescribed composition (i.e., 1.5% and 9.9%, respectively), so that the edge of the contours corresponds to the edge of the flammable gas cloud.

At 1 second after the start of the release (i.e., at 61 seconds), Figure 86 indicates that a small gas cloud is forming just aft of the mud room and another immediately starboard of the starboard overboard mud-gas rupture disk outlet. At 100 seconds after the start of the release (i.e., at 160 seconds), gas is flowing from all five release points. Figure 87 indicates that the moon pool and BOP house contain flammable gas clouds and that the aft-starboard portion of the main deck is engulfed by a flammable mixture by this time. 120 seconds after the release (i.e., at 180 seconds), the volume of the BOP house containing a flammable gas cloud has increased and a significant flammable gas cloud has developed on the forward deck, as seen in Figure 88. The size of the flammable cloud on the aft-starboard region of the main deck has also increased in size. Figure 89 shows that at 140 seconds after the release (i.e., at 200 seconds), the majority of the forward side of the main deck is engulfed by a flammable gas cloud. Figure 90 indicates that at 300 seconds after the start of the release (i.e., at 360 seconds), the BOP house and moon pool contain large flammable vapor clouds, the mid-ship regions of the aft and forward decks have reached near-stoichiometric gas concentrations, and a large flammable gas cloud has developed on the starboard-aft region of the main deck. This time corresponds to one minute after the gas flow rate through all five release points has peaked. At 360 seconds after the release began (i.e., at 420 seconds), Figure 91 shows that the gas cloud over the main deck has begun to disperse, as can be seen by comparing Figure 90 and Figure 91; however, a large portion of the main deck is still within the flammable range. To better illustrate the extents of the flammable gas cloud at the late stages of the release, Figure 92, Figure 93, and Figure 94 show 3D contours viewed looking aft from port-forward and forward from aft-starboard at 300 seconds, 360 seconds, and 450 seconds after the start of the release (i.e., at 360 seconds, 420 seconds, and 510 seconds, respectively). The outer surface of these contours represents the lower flammability limit of the gas mixture (1.5%).

Figure 95 and Figure 96 show the fuel concentration as a function of time at the supply fan locations on the forward end of the main deck and at the engine room ventilation air intake locations on the aft end of the main deck, respectively. Figure 95 shows that the gas concentration at the starboard forward supply fans (SF-36 and SF-37 reaches the flammable range about two minutes after the start of the release. The gas concentration at SF-35 on the port side of the forward deck reaches the flammable range about 2.5 minutes after the start of the release. Figure 96 shows that the gas concentration at the engine room #5 and #6 supply air intakes (SF-05 and SF-06, respectively) enters the flammable range between 60 and 90 seconds after the start of the release. At 300 seconds after the start of the release, the gas concentration at these locations peaks at over 20%, well above the upper flammability limit of the gas mixture (9.9%). This corresponds to roughly one minute after the gas flow rate through all five release points has peaked. After about 50 more seconds, the gas concentration at SF-05 and SF-06 re-enters the flammable range. At this time, the concentration at the ventilation air intakes for engine rooms #3 through #6 (SF-03, SF-04, SF-05, and SF-06) are within the flammable range and remain so for over two minutes.

Figure 97 shows a column graph depicting the maximum gas concentration recorded at monitor locations 1.5 meters above the main deck. This vertical plane is one to two meters below the engine room supply air intakes on the aft side of the main deck. The x,y location (0,0) on this plot corresponds to the center of the riser bore. Note that flammable concentrations are achieved over almost the entire deck. High concentrations, exceeding the upper flammability limit are achieved at mid-ship and at the aft-starboard region of the deck.

These results demonstrate that the release profile modeled in scenario A outlined in Table 5 and depicted in Figure 85 is capable of developing a flammable gas cloud throughout the moon pool and BOP house, over the drill floor, and over the vast majority of the main deck. In particular, flammable gas concentrations are obtained at the engine room #3 through #6 ventilation air intakes. It is feasible that given this release scenario, a flammable gas mixture could have formed within these four engine rooms.

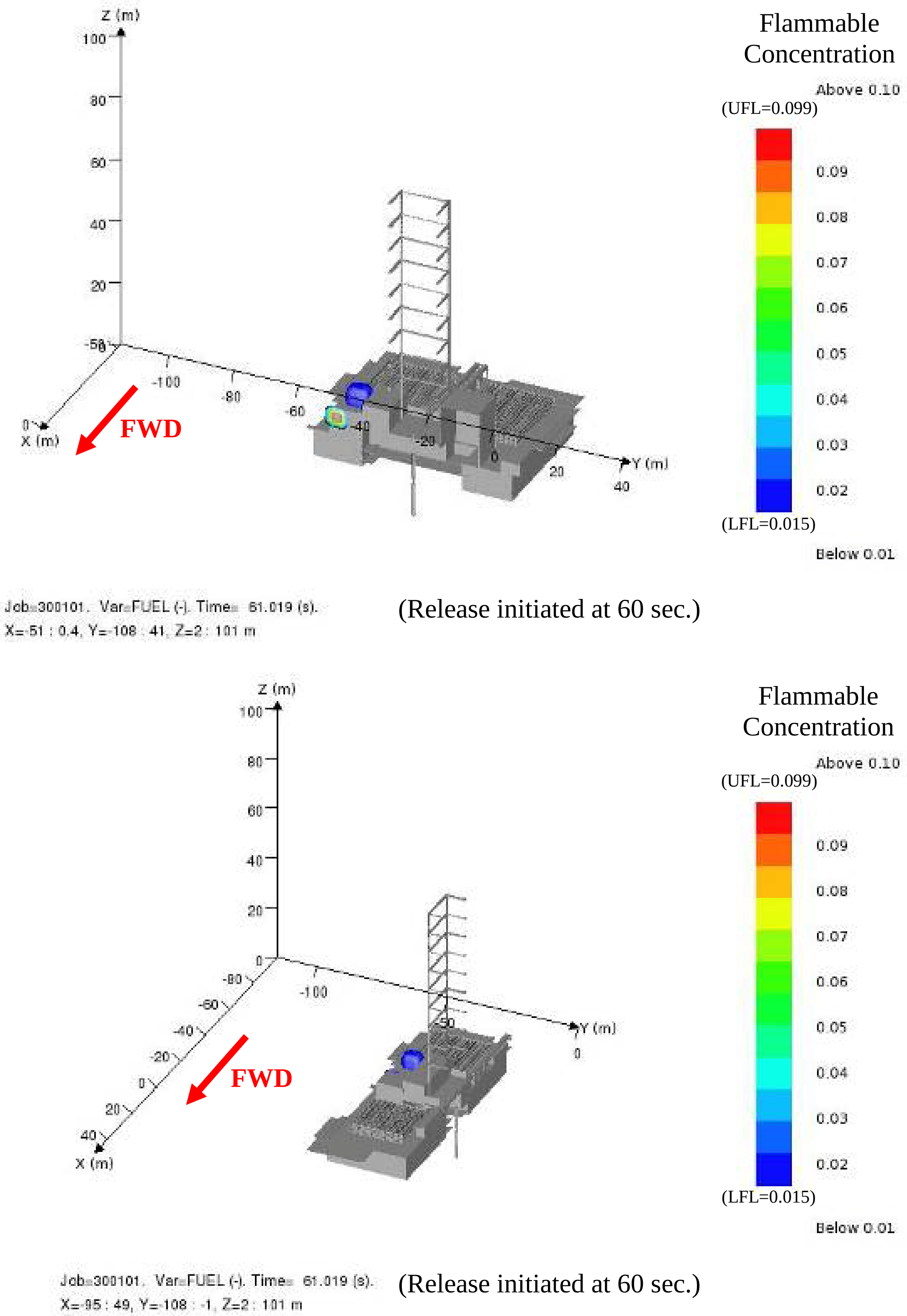


Figure 86. Flammable Cloud at 61 seconds (Scenario A)

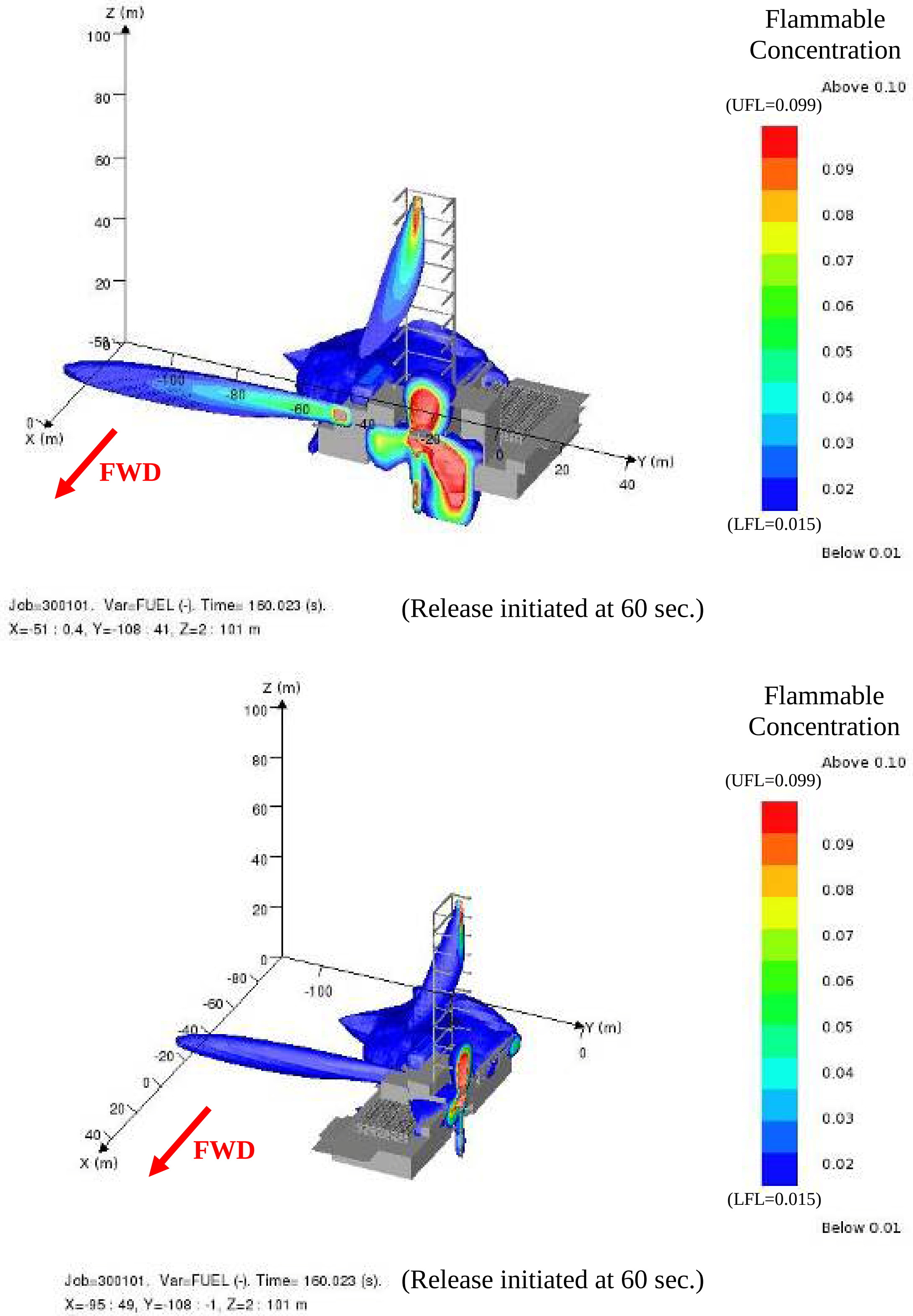


Figure 87. Flammable Cloud at 160 seconds (Scenario A)

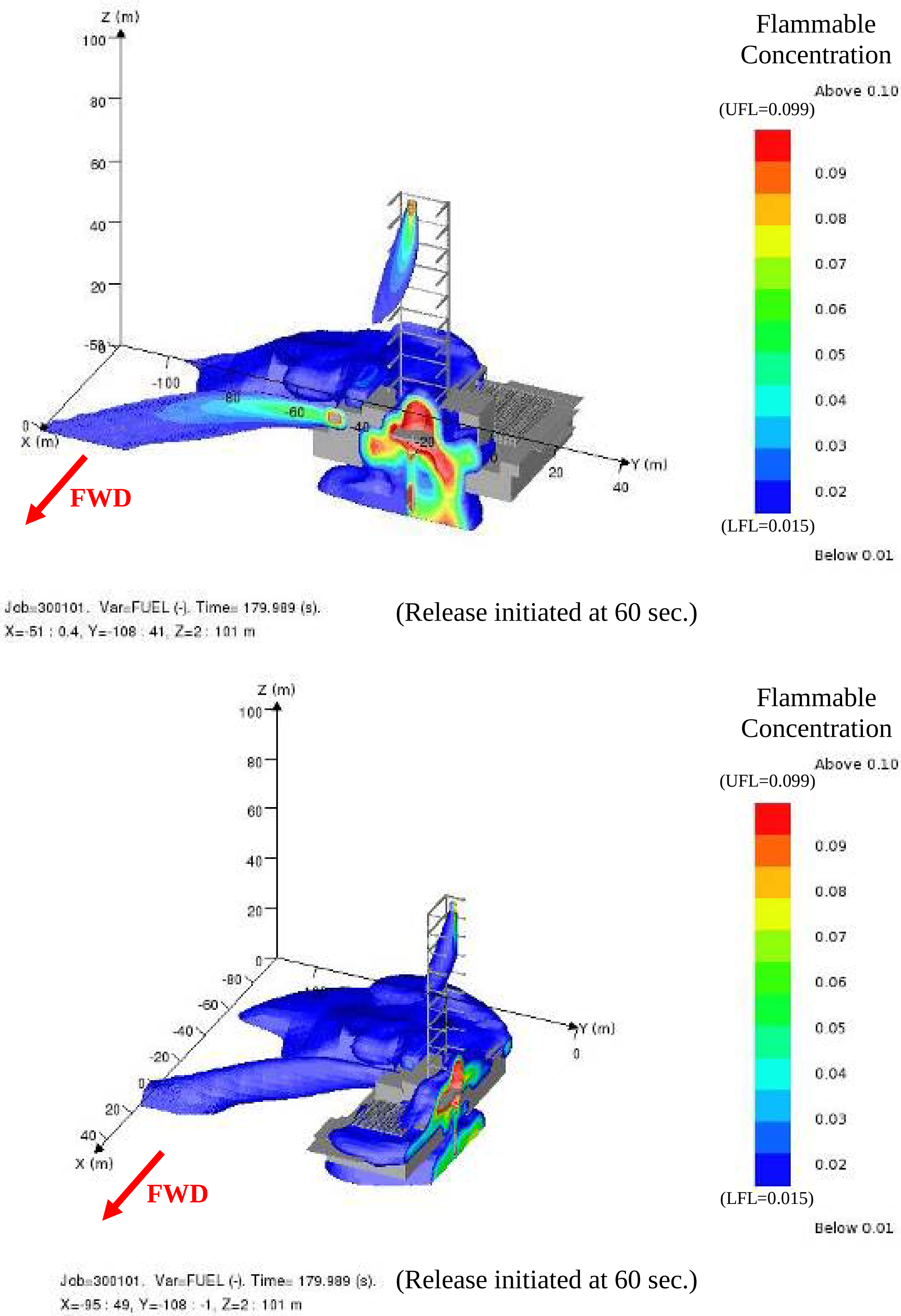


Figure 88. Flammable Cloud at 180 seconds (Scenario A)

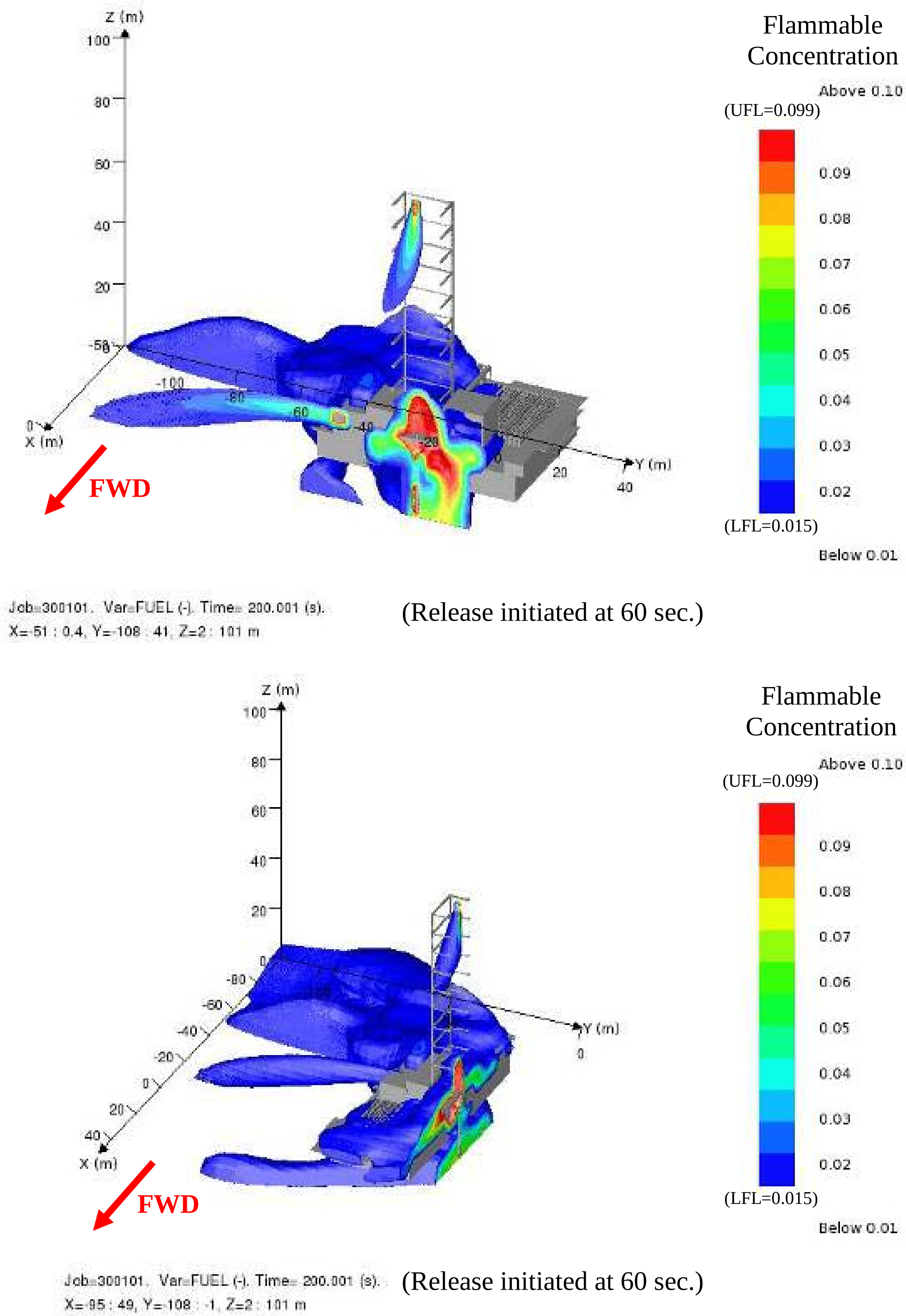
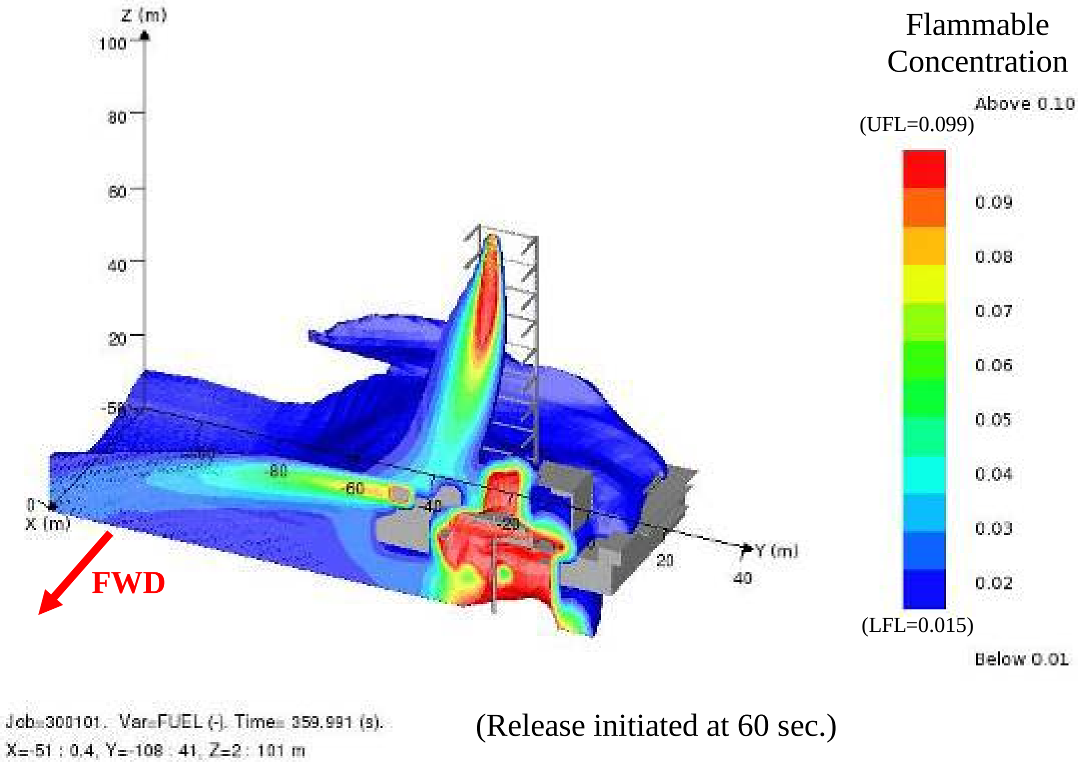


Figure 89. Flammable Cloud at 200 seconds (Scenario A)



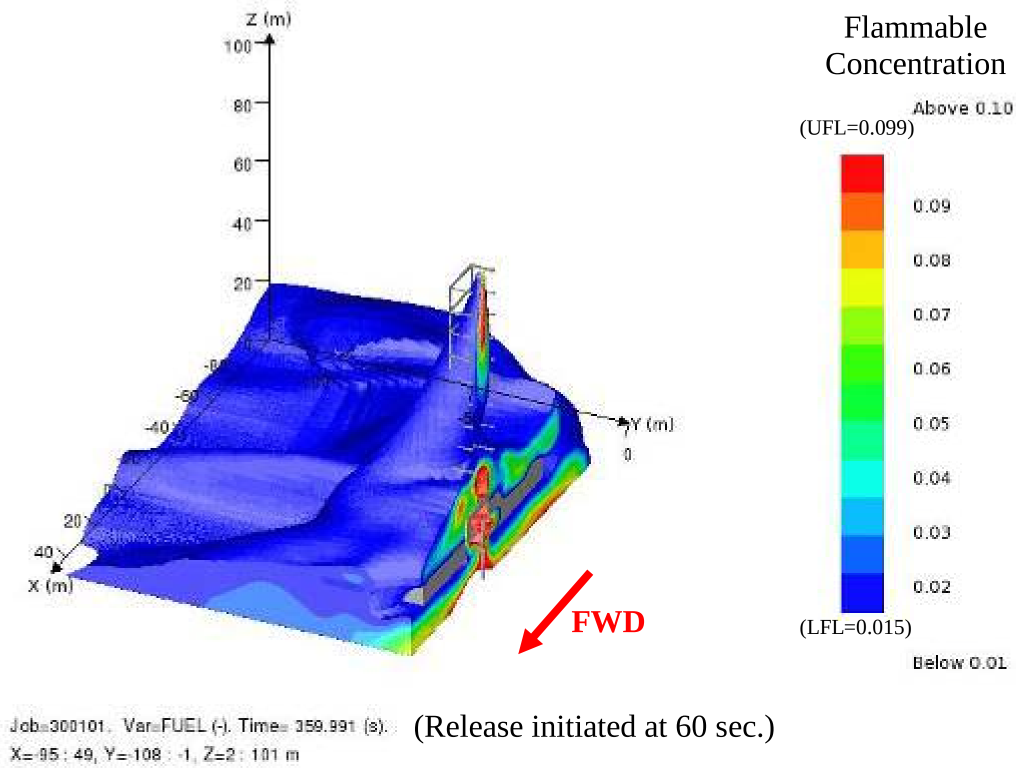


Figure 90. Flammable Cloud at 360 seconds (Scenario A)

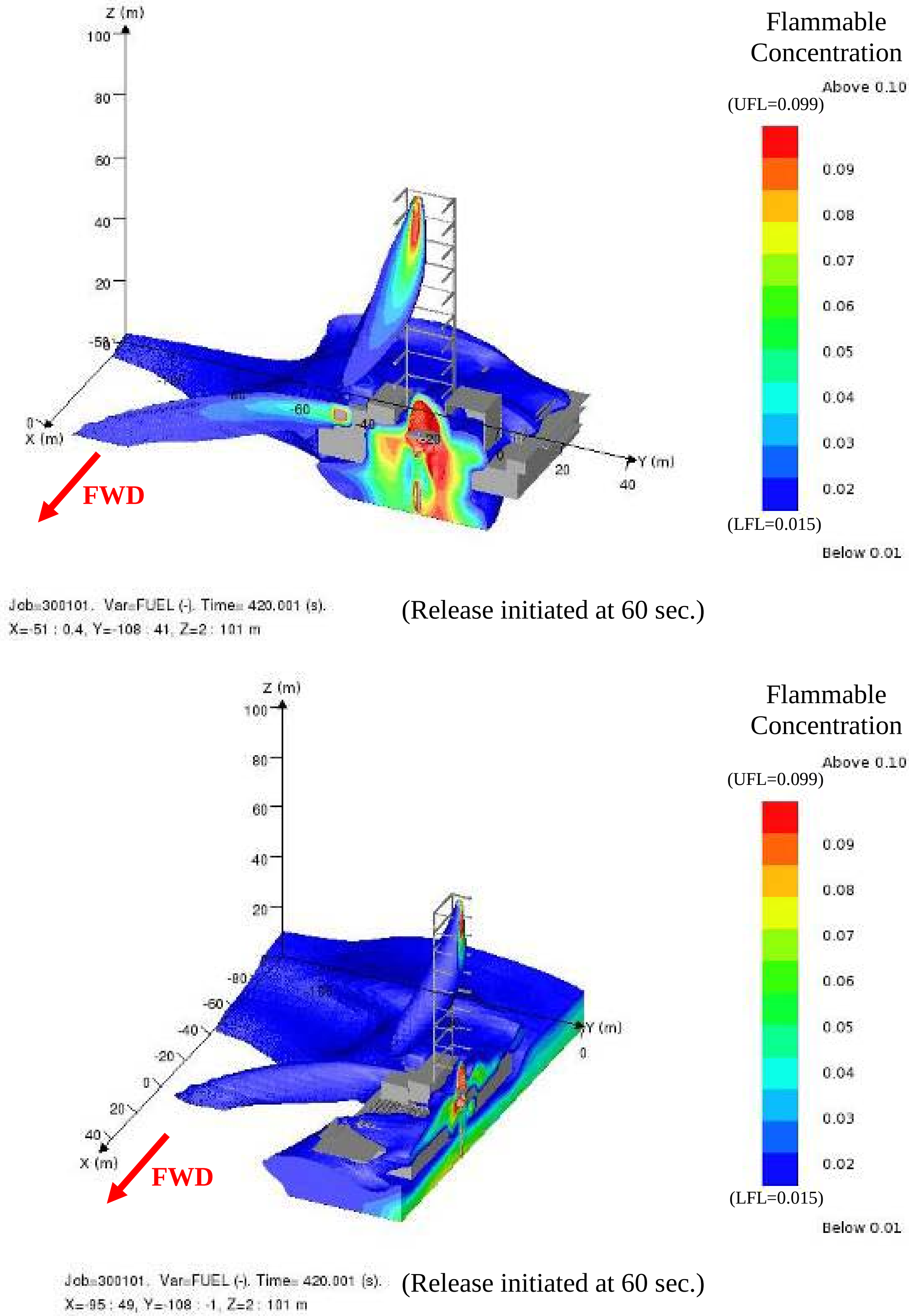


Figure 91. Flammable Cloud at 420 seconds (Scenario A)

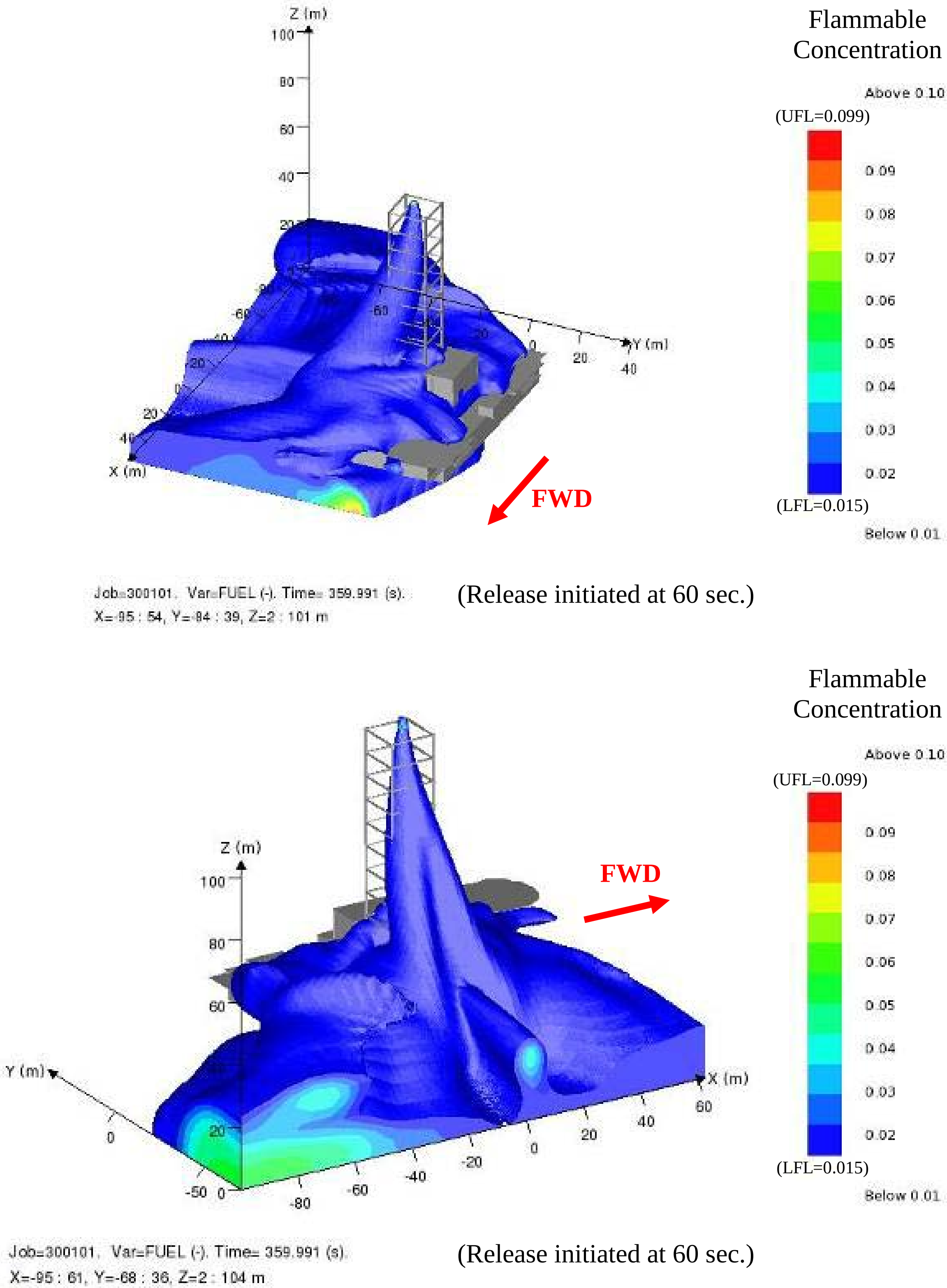
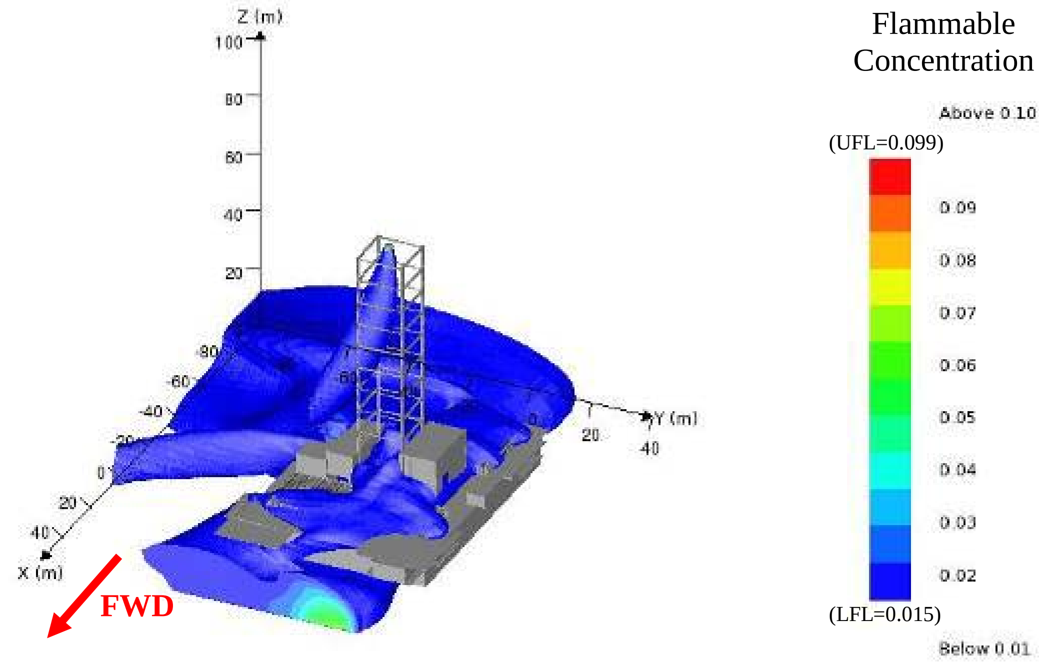
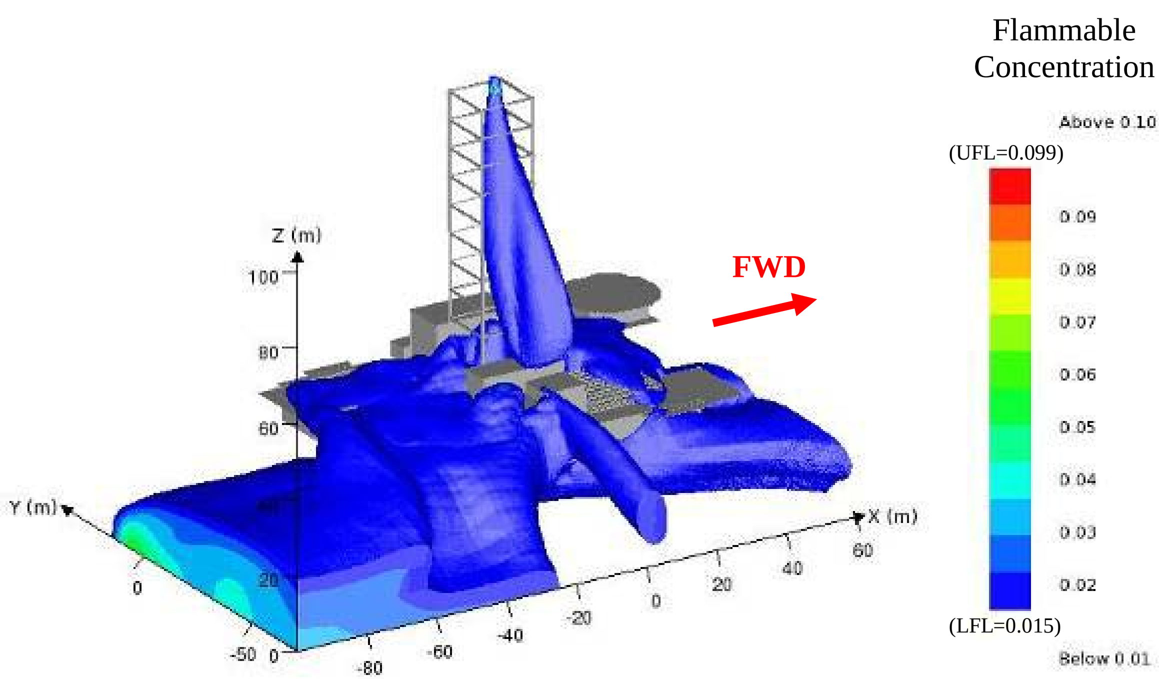


Figure 92. Flammable Cloud at 360 seconds (3D, Scenario A)

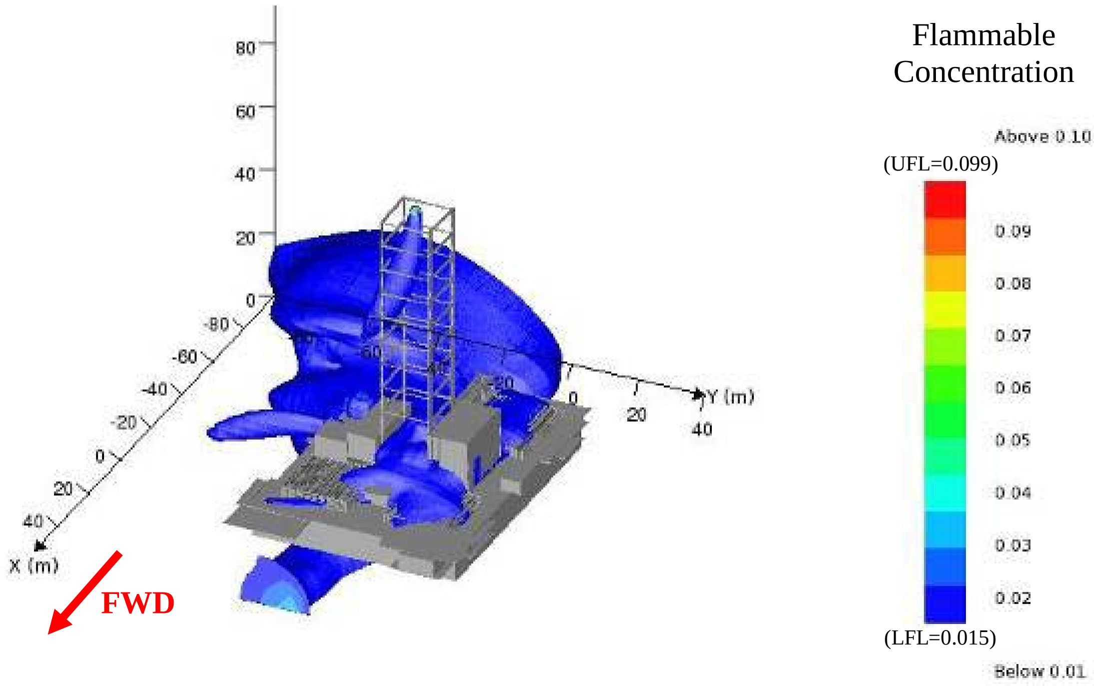


(Release initiated at 60 sec.)



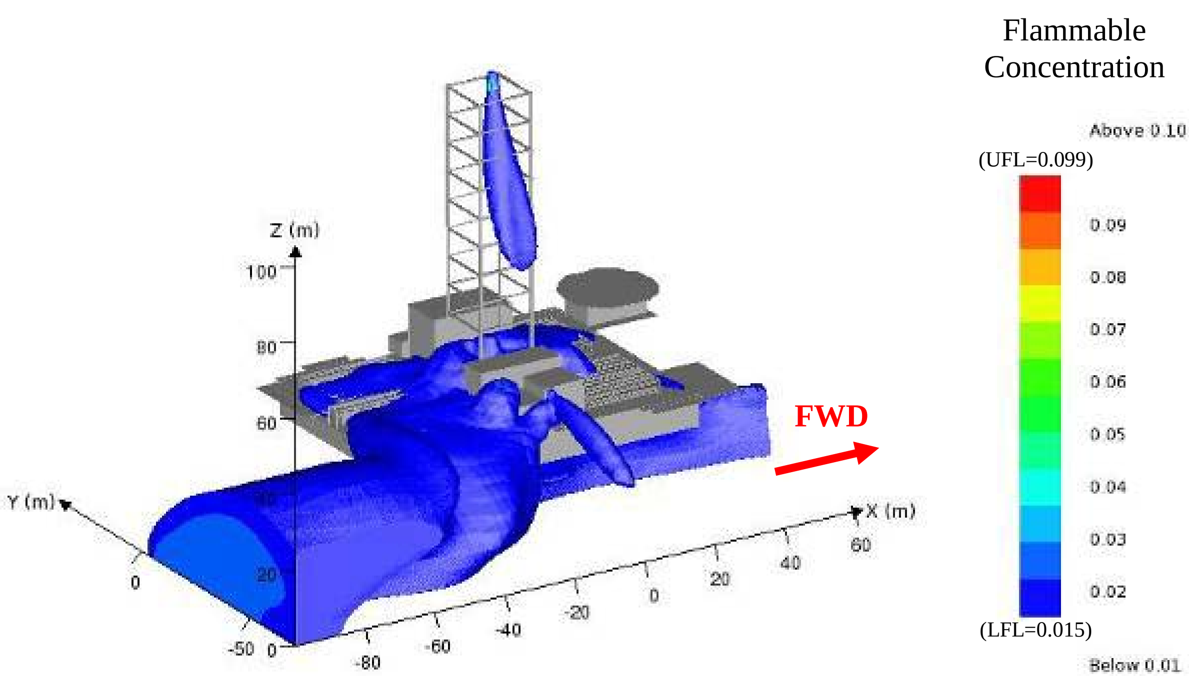
(Release initiated at 60 sec.)

Figure 93. Flammable Cloud at 420 seconds (3D, Scenario A)



Job=300101, Var=FUEL (-), Time= 509.988 (s),
X=-95 : 54, Y=-84 : 39, Z=2 : 101 m

(Release initiated at 60 sec.)



Job=300101, Var=FUEL (-), Time= 509.988 (s),
X=-95 : 61, Y=-68 : 36, Z=2 : 104 m

(Release initiated at 60 sec.)

Figure 94. Flammable Cloud at 510 seconds (3D, Scenario A)

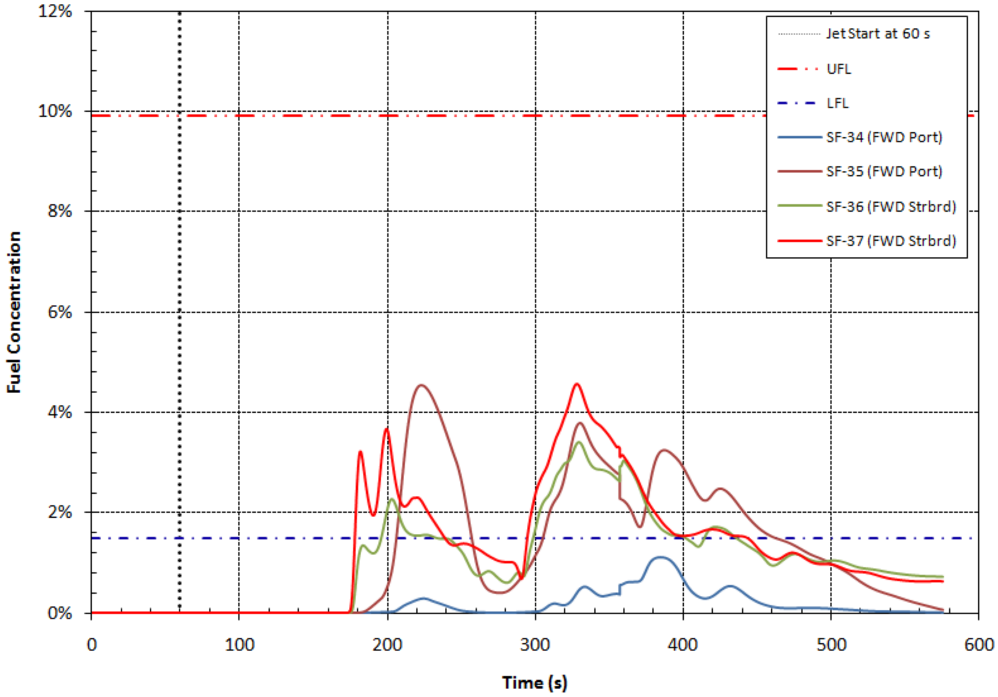


Figure 95. Forward Deck Ventilation Intake Flammable Gas Concentration History (Scenario A)

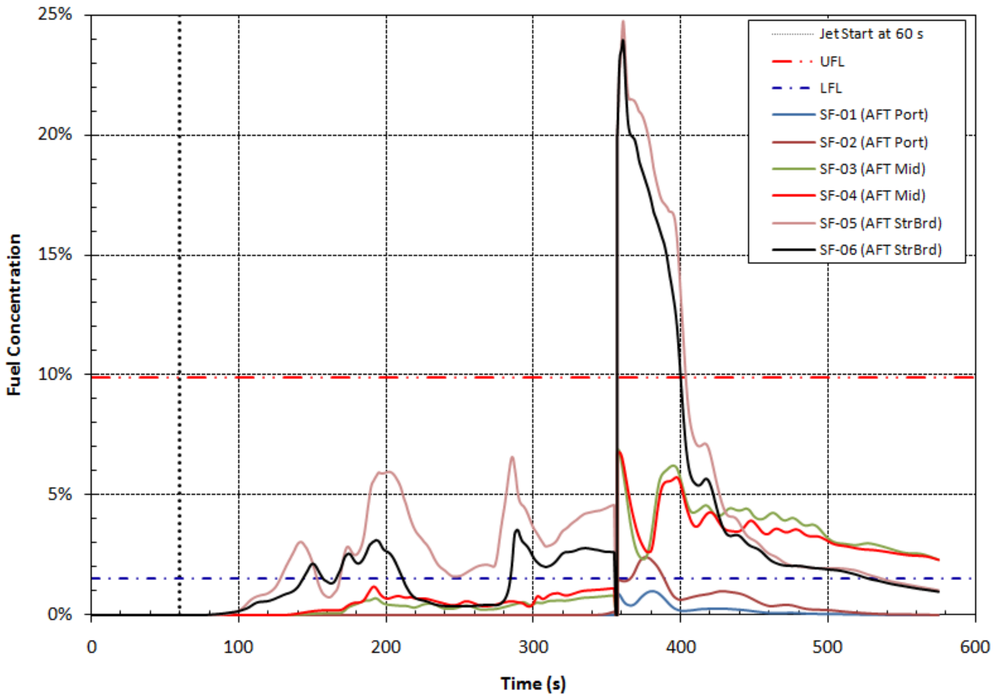


Figure 96. Engine Room Ventilation Intake Flammable Gas Concentration History (Scenario A)

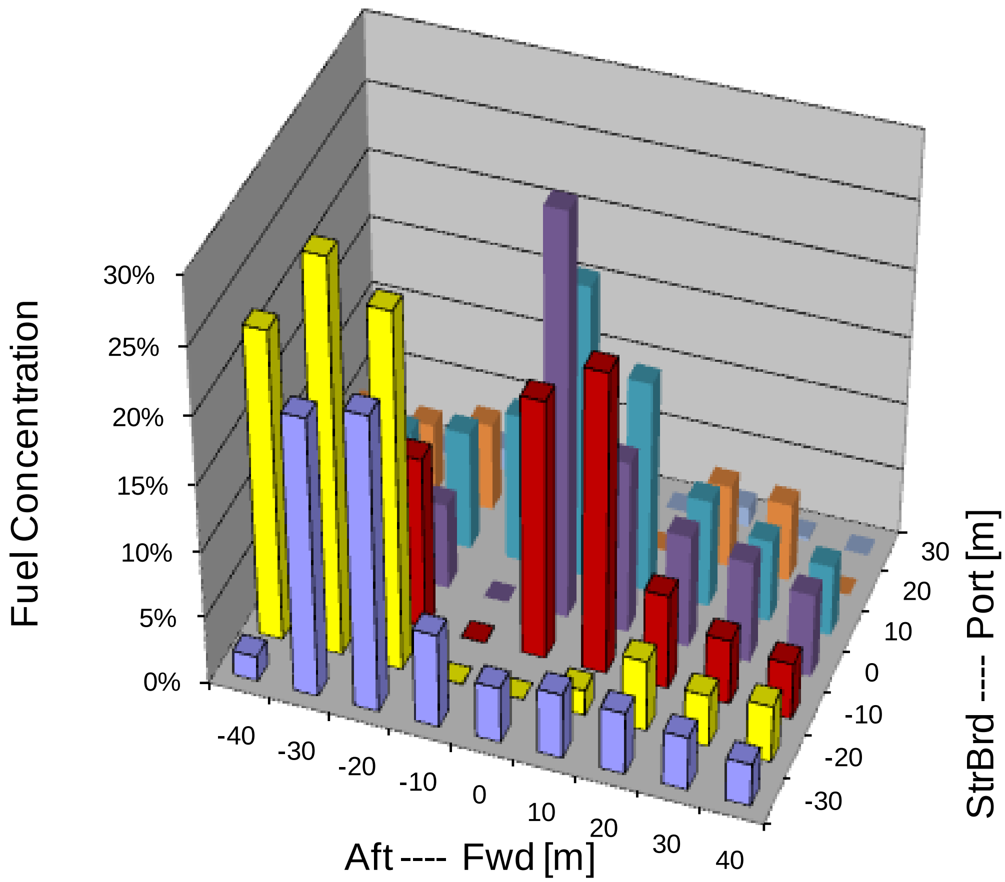


Figure 97. Maximum Gas Concentration 1.5 m above Main Deck (Scenario A)

6.2 Scenario B

The Scenario B release described previously in Section 4.4.8 was evaluated with the wind from port (to starboard) at 2 m/s, as was the case for the Scenario A release evaluation. As before, the simulation was first run for 60 seconds without gas release to establish the flow field due to the wind. The ventilation sources and sinks listed in Table 4 and shown in Figure 70 and Figure 71 were in operation for the duration of the simulation, including this 60 second “start-up” period. The wind field immediately prior to the gas release in the xy-plane located three meters above the main deck (representative of the engine room supply air louvers) is exactly as it was for Scenario A, as shown above in Figure 84.

The release of flammable gas was again taken to begin at 60 seconds and followed the Scenario B flow rate profile shown in Figure 53. This figure has been duplicated below on a mass flow rate basis as Figure 98 for the convenience of the reader. The total duration of the release was 360 seconds (6 minutes). As noted previously, a total of 0.33 MMscf of gas was released.

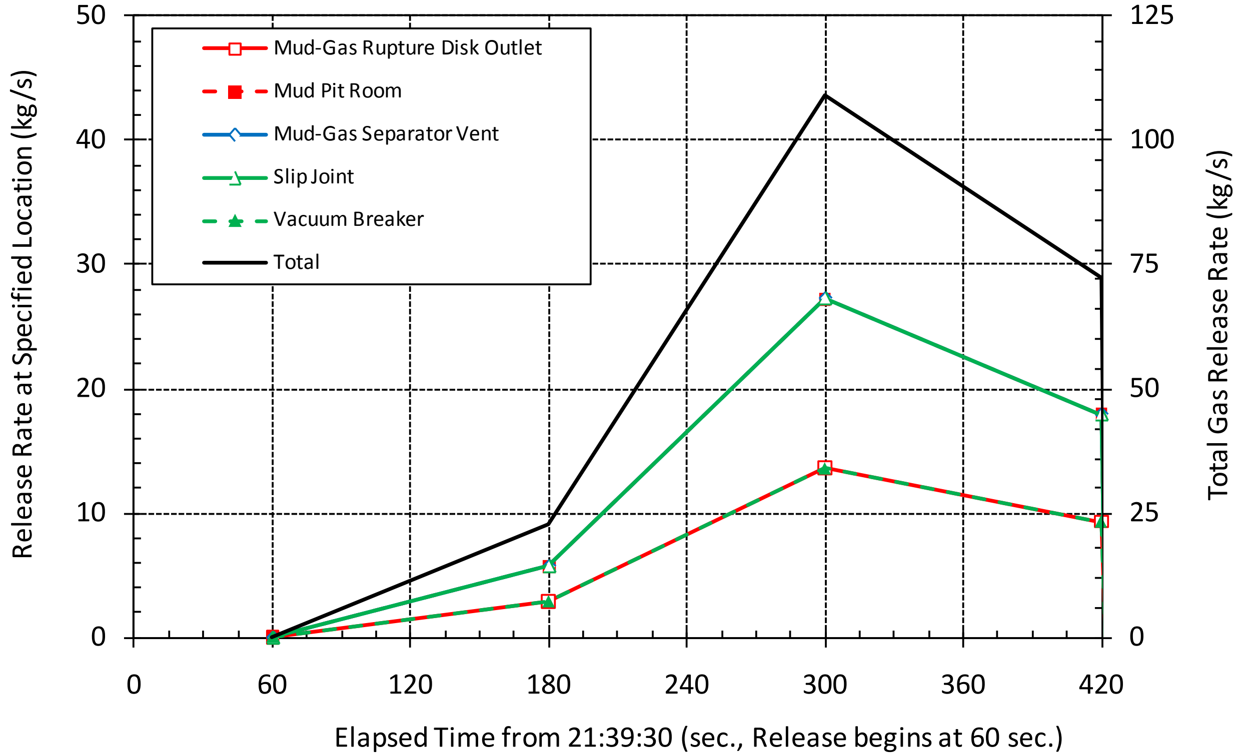


Figure 98. Scenario B Gas Flow Rate (kg/s) as a Function of Time from Each Release Point

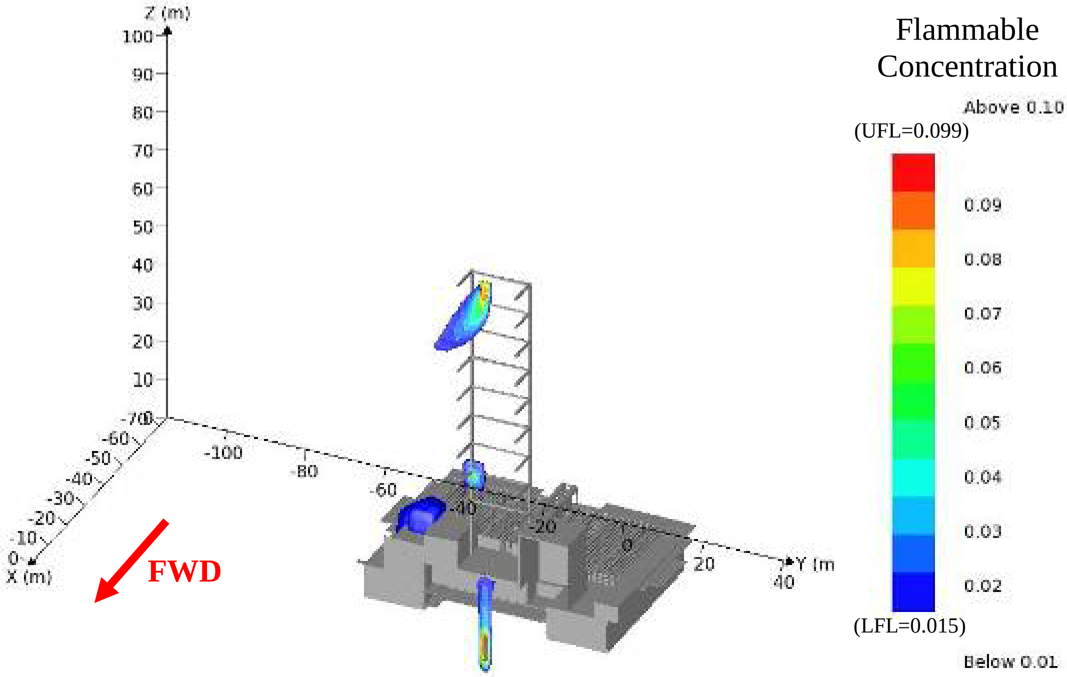
The flammable gas cloud developed due to the release profile shown in Figure 98 is shown at 60, 180, 240, and 300 seconds after the release (i.e., at 120, 240, 300, and 360 seconds) in Figure 99 through Figure 102. These figures provide a cut plane through the well center along the starboard-port plane looking aft and a cut plane through the well center along the forward-aft plane looking aft-starboard. The upper and lower end of the contours shown in the figure correspond to the fuel mixture's lower flammability limit (LFL) and upper flammability limit (UFL) for the prescribed composition (i.e., 1.5% and 9.9%, respectively), so that the edge of the contours corresponds to the edge of the flammable gas cloud.

At 60 seconds after the start of the release (i.e., at 120 seconds), Figure 99 shows that a small gas cloud is forming just aft of the mud room and another starboard of the derrick near the starboard diverter. At 180 seconds after the start of the release (i.e., at 240 seconds), Figure 100 shows that the moon pool and BOP house contain flammable gas clouds and that the aft-starboard portion of the main deck and the drill floor are engulfed by a flammable mixture. 240 seconds after the release began (i.e., at 300 seconds), the volume of the BOP house containing a flammable gas cloud has increased and a higher concentration gas cloud has formed within the moon pool, as can be seen in Figure 101. The flammable cloud on the aft-starboard region of the main deck has dispersed further starboard off the side of the ship under the influence of the background wind field by this point in time. Figure 102 shows that at 300 seconds after the release began (i.e., at 360 seconds), at which point the release rate has decreased from the peak value, the moon pool and BOP house still contain flammable concentrations of gas. However, the gas cloud that had formed at the starboard-aft end of the main deck has largely been blown off the ship by the wind by this point in time. To better illustrate the extents of the flammable gas cloud at the peak release rates, Figure 103 and Figure 104 show 3D contours viewed looking aft from port-forward and forward from aft-starboard at 180 seconds and 240 seconds after the start of the release (i.e., at 240 seconds and 300 seconds, respectively). The outer surface of these contours represents the lower flammability limit of the gas mixture (1.5%). The location of the supply air intake for engine room #4 (SF-04) is also shown on these figures. Note that the extent of the flammable gas cloud approaches the starboard side of the catwalk at the aft end of the ship. Of particular interest for the purposes of this evaluation, the flammable gas concentration reaches the lower flammability limit within a very short distance of SF-04 at 240 seconds into the release.

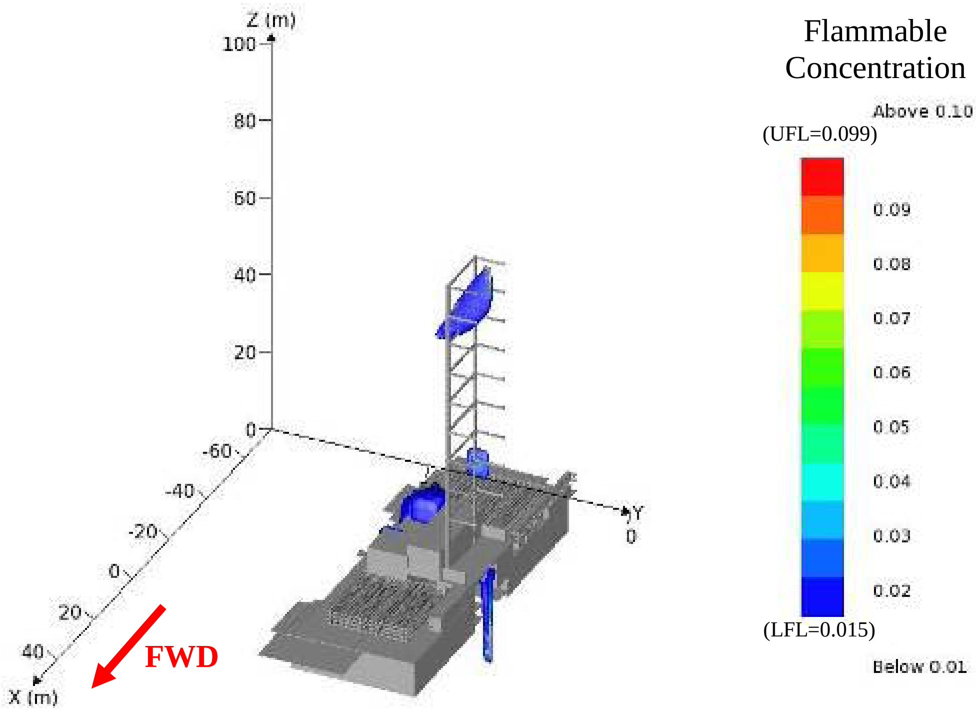
Figure 105 and Figure 106 show the fuel concentration as a function of time at the supply fan locations on the forward end of the main deck and at the engine room ventilation air intake locations on the aft end of the main deck, respectively. Figure 105 shows that a flammable gas cloud does not develop over the duration of the Scenario B release at the forward supply air intakes. Figure 106 shows that the fuel gas concentration at the engine room #5 supply air intake (SF-05) enters the flammable range approximately 170 seconds after the start of the release and remains flammable for over 140 seconds. The fuel gas concentration at the engine room #6 supply air intake (SF-06) reaches the lower flammable limit (1.5%) approximately 250 seconds after the start of the release and falls back below the lower flammable limit less than 10 seconds thereafter.

At the release rates assumed for Scenario B, the flammable gas concentration is not predicted to exceed the lower flammability limit at the engine room #3 or #4 supply air intakes (SF-03 and SF-04, respectively). However, Figure 103 and Figure 104 indicate that a flammable cloud does develop in close proximity to SF-04. It should be noted in this regard that variations in wind direction and wind speed were not considered in this evaluation and the actual arrangement of non-permanent objects on the main deck is not known and was therefore not reflected in the solid model. It is expected that such factors could perturb the flow field and flammable gas dispersion behavior around the location of the supply air intakes sufficiently that the flammable gas concentration at SF-03 and SF-04 could exceed the lower flammability limit.

These results demonstrate that the Scenario B release is capable of developing a flammable gas mixture at the engine room #5 and #6 ventilation air intakes. It is also possible that the flammable gas concentration at the engine room #3 and #4 ventilation air intakes could have exceeded that lower flammability limit, even at the lower total release rate associate with Scenario B.

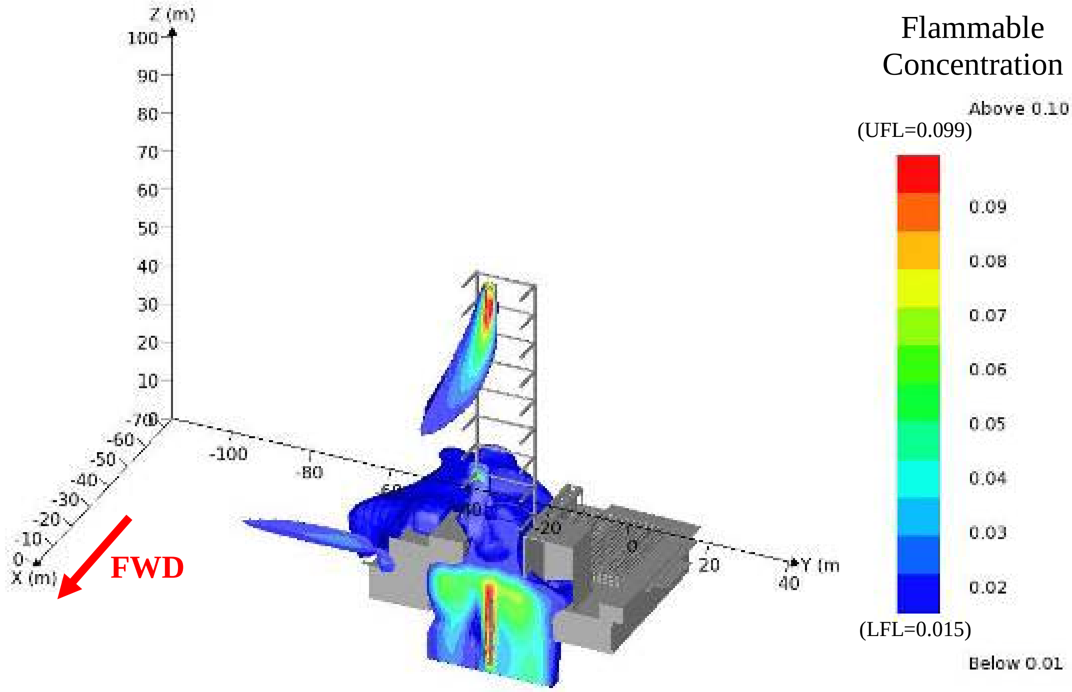


(Release initiated at 60 sec.)

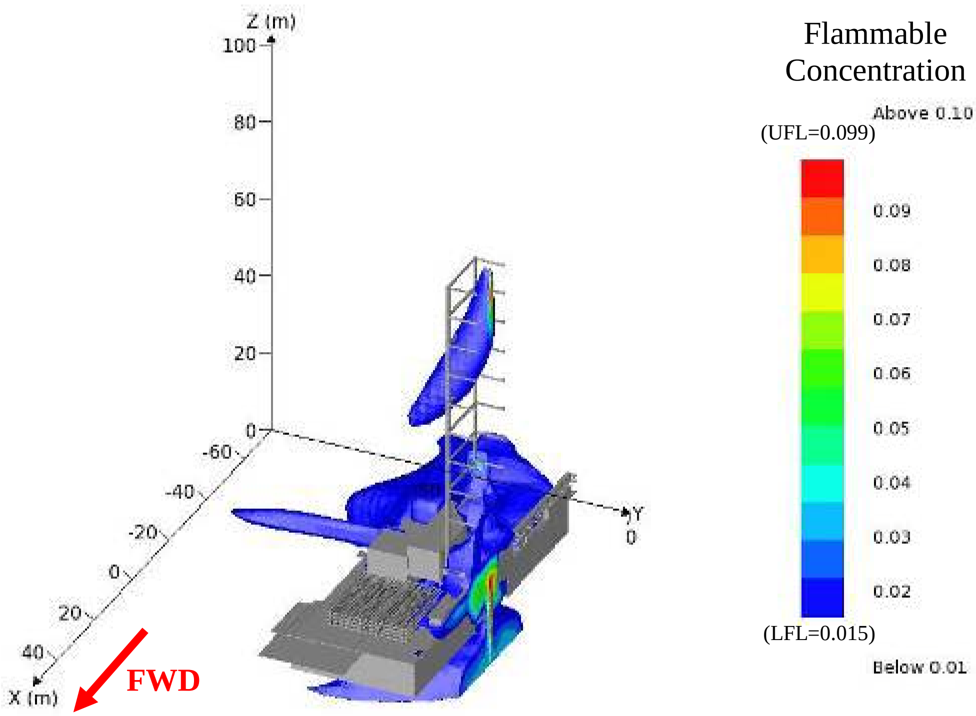


(Release initiated at 60 sec.)

Figure 99. Flammable Cloud at 120 seconds (Scenario B)

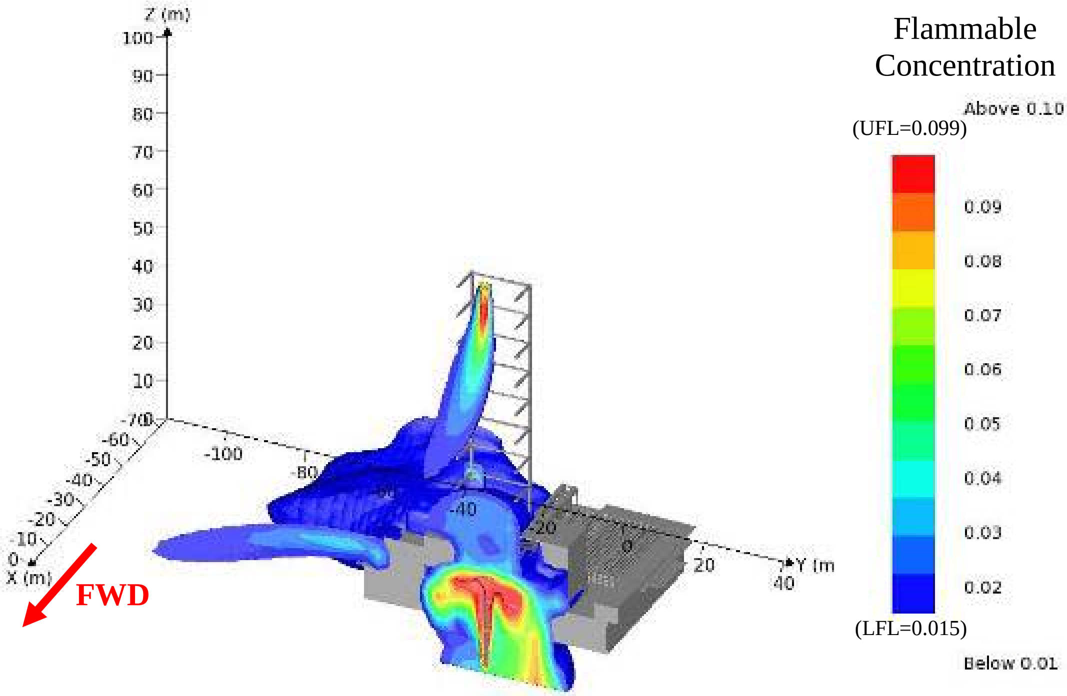


(Release initiated at 60 sec.)

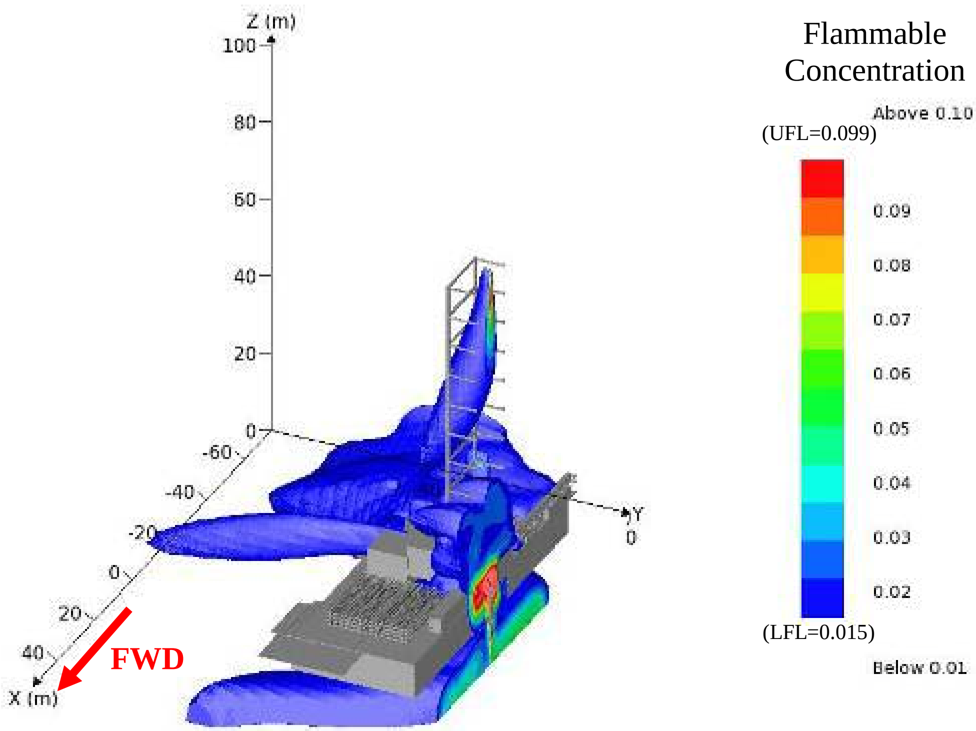


(Release initiated at 60 sec.)

Figure 100. Flammable Cloud at 240 seconds (Scenario B)

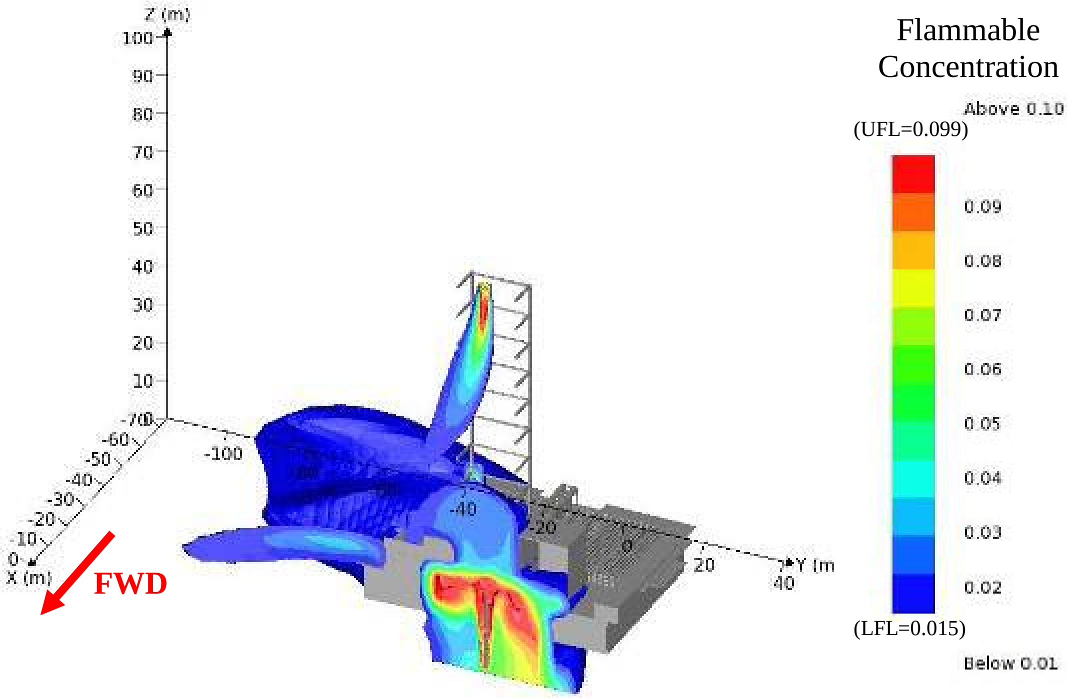


(Release initiated at 60 sec.)

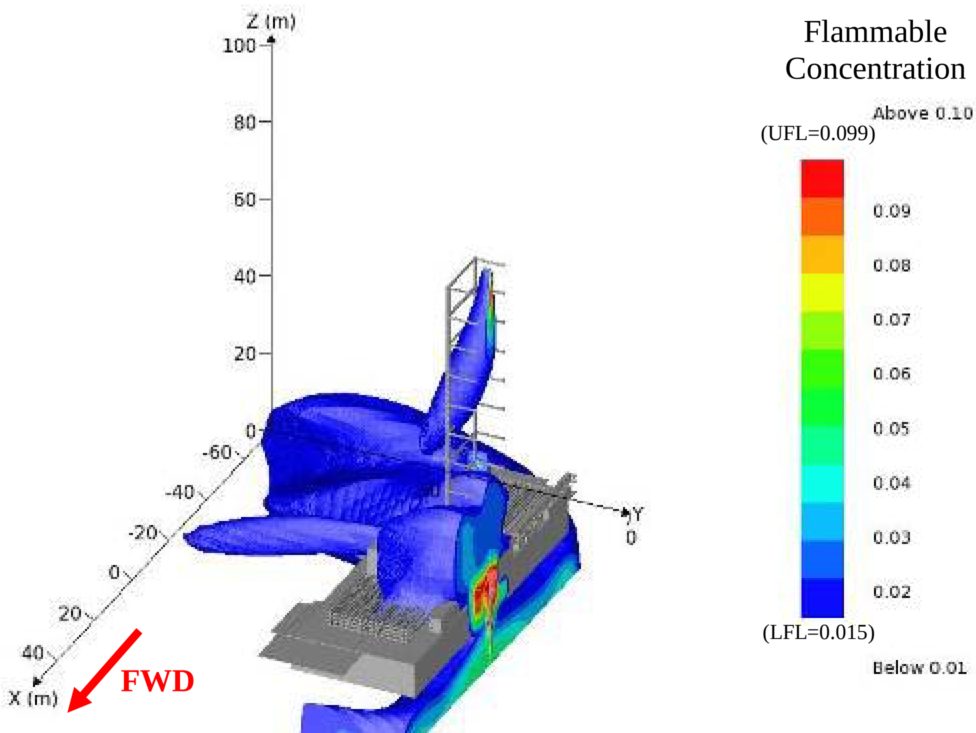


(Release initiated at 60 sec.)

Figure 101. Flammable Cloud at 300 seconds (Scenario B)



(Release initiated at 60 sec.)



(Release initiated at 60 sec.)

Figure 102. Flammable Cloud at 360 seconds (Scenario B)

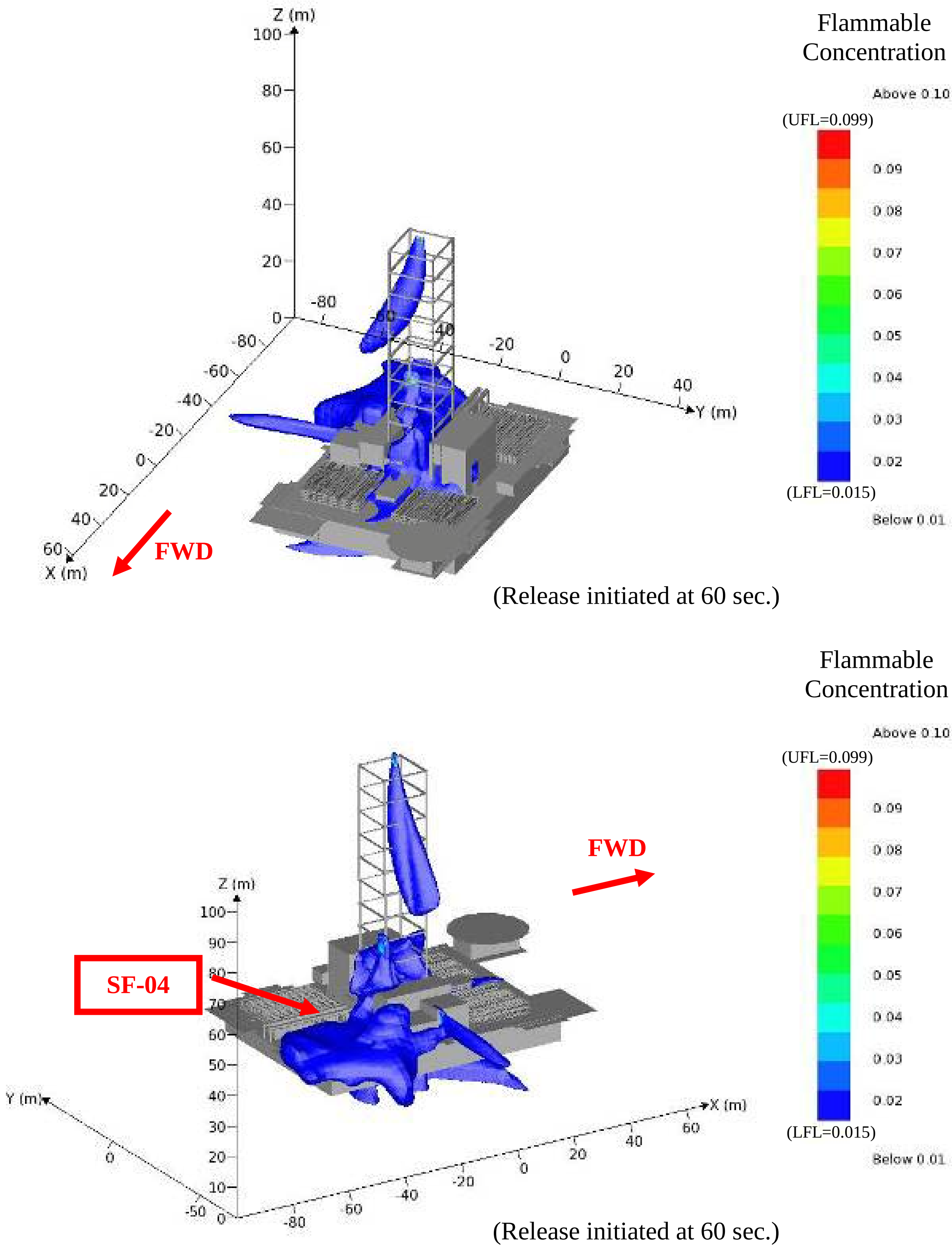


Figure 103. Flammable Cloud at 240 seconds (3D, Scenario B)

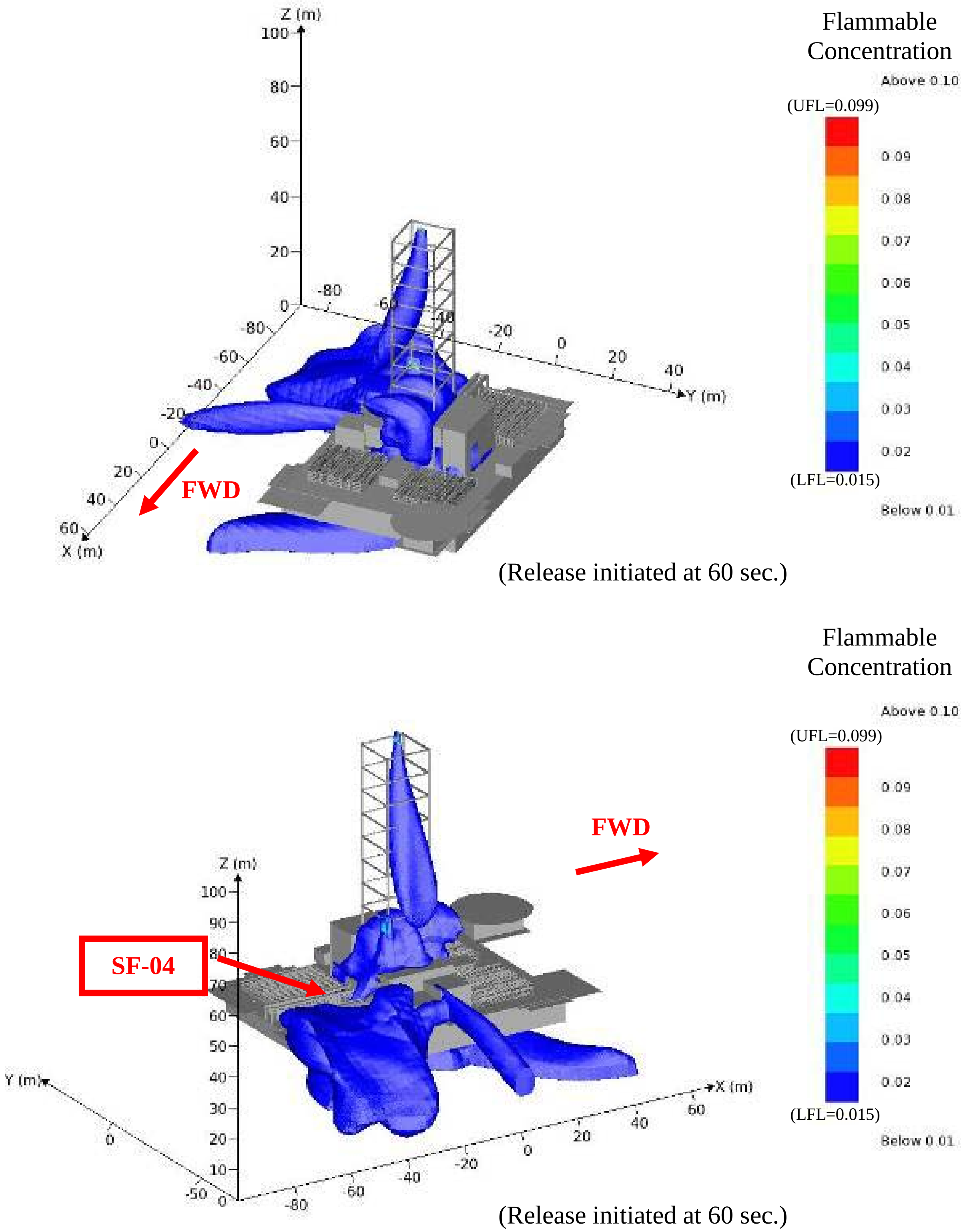


Figure 104. Flammable Cloud at 300 seconds (3D, Scenario B)

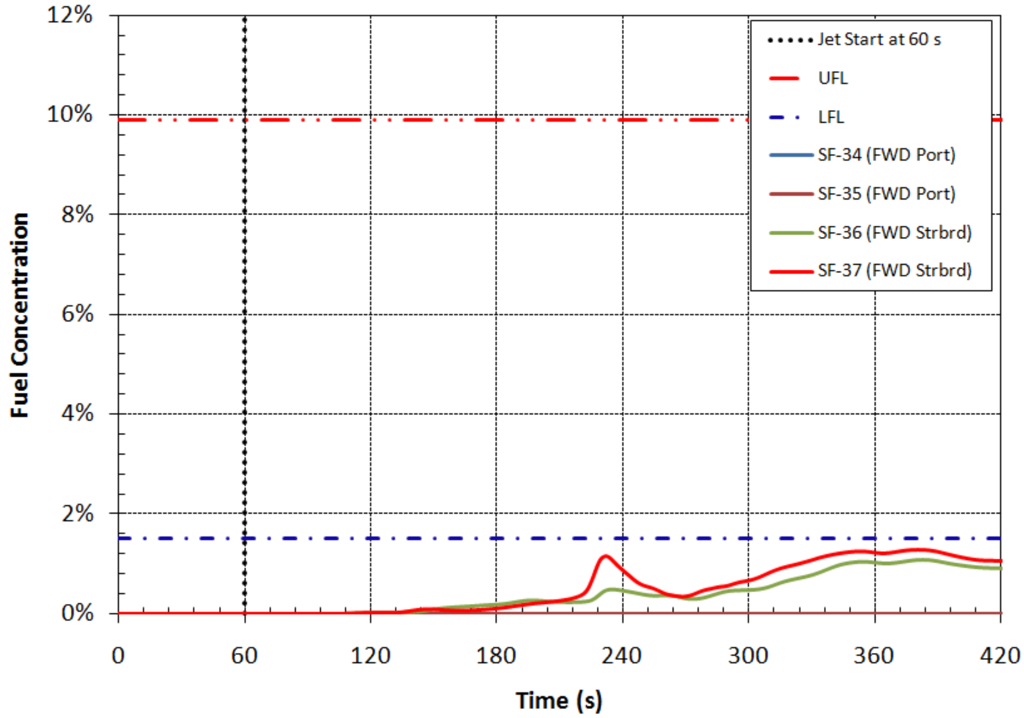


Figure 105. Forward Deck Ventilation Intake Flammable Gas Concentration History (Scenario B)

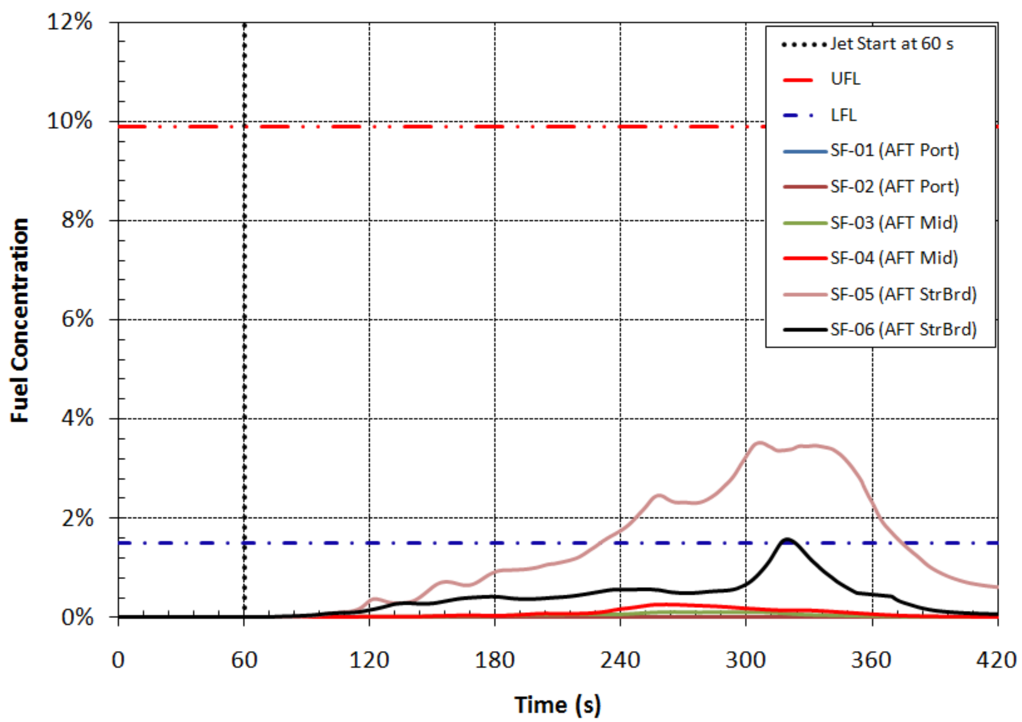


Figure 106. Engine Room Ventilation Intake Flammable Gas Concentration History (Scenario B)

APPENDIX A.
(DESCRIPTION OF FLACS)

FLACS (FLame ACceleration Simulator) is a CFD (Computational Fluid Dynamics) tool developed in the early 1980s by the Christian Michelsen Research Institute (the FLACS development group is now incorporated into GexCon AS) in Norway, primarily for simulating dispersion of gas leaks and subsequent explosions in offshore oil and gas production platforms. The latest version of the FLACS has many more applications such as explosion mitigation measures (grating, vent panel and opening, waterspray, etc.) and safety and risk studies of land-based process industries.

FLACS solves compressible Navier-Stokes equations on a 3-D Cartesian grid by using a finite-volume method. Second order schemes (Kappa schemes with weighting between 2nd order upwind and 2nd order difference, delimiters for some equations) are employed to solve the conservation equations for mass, momentum, enthalpy, turbulence and species/combustion. The equations are closed with a k-ε turbulence model. The SIMPLE pressure correction method[A1]is applied and extended for compressible flows with source terms of the compression work in the enthalpy equation. Hjertager[A2] describes the basic equations used in the FLACS model. The explosion experiments to develop and validate FLACS initially have also been published[A3,A4].

FLACS uses a "beta" flame model wherein the reaction zone becomes 3-5 grid cells thick[A5]. The burning velocity is primarily controlled by diffusion of reaction products. At the beginning of the simulation, a flame library determines the laminar burning velocity as a function of the gas mixture, equivalence ratio, pressure, temperature, etc. Initial "quasi-laminar" flame wrinkling then increases the burning velocity with distance. A turbulent burning velocity replaces the velocity as turbulence increases. Models for turbulent quenching, effect of water deluge, inert gas dilution and more have also been implemented. The real flame area is described properly and corrected for curvature at scales equal to and smaller than the reaction zone. All flame wrinkling at scales less than the grid size is represented by sub-grid models, which is important for flame interaction with objects smaller than the grid size.

The proper representation of geometry (obstacles, buildings or facilities) is a key aspect of the development of the FLACS code. A so-called distributed porosity concept was developed as a compromise between the need to characterize the geometric details and the need to have the code run in a reasonable time. Obstacles such as structures and pipes are represented as area porosities (the opposite of blockages) on control volume (CV) faces and are represented as volume porosities in the interior of the CV. CV surfaces and CV volumes are each either fully open, fully blocked, or partly blocked. For the partly blocked surfaces or volumes, the porosity is defined as the fraction of the area/volume that is available for fluid flow. The resulting porosity model is used to calculate the flow resistance terms, the turbulence source terms from small objects, and

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A1) Patankar, S.V., 1980. *Numerical Heat Transfer and Fluid Flow*, Hemisphere Publications. New York

A2) Hjertager, B.H., 1985. Computer simulation of turbulent reactive gas dynamics. *J. Model. Identification Control*. 5:211-236

A3) Hjertager, B.H., Bjørkhaug, M. and Fuhre, K. 1985. Explosion propagation of non-homogeneous methane-air clouds inside an obstructed 50m3 vented vessel. *J. Haz. Mater*. 19:139-153

A4) Hjertager, B.H., Bjørkhaug, M. and Fuhre, K. 1987. Gas explosion experiments in 1:33 and 1:5 scale offshore separator and compressor modules using stoichiometric homogeneous fuel/air clouds. *J. Loss Prevention Proc. Ind.* 1:197-205

A5) Arntzen, B.A., 1998. Modeling of turbulence and combustion for simulation of gas explosions in complex geometries. PhD Thesis, Norwegian Univ. of Sci. and Tech. (NTNU), Trondheim, Norway the flame speed enhancement arising from flame folding in the sub-grid wake. In FLACS, different drag coefficients are used for cylindrical and rectangular sub-grid objects, and significant drag and turbulence are generated only behind an object, and not along an object that partly blocks a CV. Therefore, FLACS can handle all kinds of complicated geometries using a Cartesian grid. Large objects and walls will be represented on-grid; smaller objects will be represented sub-grid. Sub-grid objects will contribute to flow resistance, turbulent generation, and flame folding (explosions) in the simulation.

Figure A 1. Typical FLACS Geometry and Simulation