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MODU Mooring Reliability Analysis for Hurricane Condition in the Gulf of Mexico

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Abstract

This paper presents a probabilistic study of various Gulf of Mexico (GoM) MODU mooring systems that was performed as part of the MODU Mooring JIP (Joint Industry Project). The intent was to determine the relative changes in reliability between different types of MODUs, with different mooring systems, in different water depths, designed for different hurricane conditions and located at different regions in the Gulf. In addition, the effects of assuming reduced mooring line strength were investigated.

Twenty cases were selected which cover four different classes of MODUs, four different types of mooring systems, three different numbers of mooring lines, as well as three different water depths. These base cases were chosen so that trends or differences between different hull shapes and mooring systems could be identified. These twenty base cases are further expanded into sixty cases according to location in the Gulf as well as the return period used to design the mooring system.

The results indicate that on average the “notional” (i.e., relative) annual failure probability of mooring line failure decreases by one order of magnitude when increasing the MODU mooring system design return period from 10-yr to 50-yr. Two orders of magnitude decrease are observed if the design return period is increased from 10-yr to 100-yr. In addition to the above findings, reliability sensitivity to four different GoM Metocean regions is also provided. Redundancy of the mooring system for 8, 12 and 16-lines is also examined in terms of the additional reliability gained by the extra lines.

Introduction

The probabilistic reliability approach was performed using an updated procedure that was originally developed in prior work by DeepStar [1]. The results can be used by operators, drilling contractors, API work groups and regulators alike to understand, on a comparative basis, the performance of various MODUs and mooring systems.

A base set of 20 separate MODU and associated mooring cases were evaluated as shown in the first twenty cases of the matrix in Table 1. These selected twenty base cases cover four MODUs (or MODU classes), four types of mooring systems, three numbers of mooring lines and three water depths. The footnotes of Table 1 provide definitions of these cases. These base cases were chosen so that trends or differences between different hull shapes and mooring systems can be identified.

This base set of cases was then further defined into a larger set of 60 according to location in the Gulf as well as the return period used to design the mooring system. The Gulf locations were defined as the Central, West Central and West according to MODU JIP metocean study [5] and the latest API guideline [6], and the design return periods were defined as 10, 25, 50 and 100 year. The remainder of Table 1 shows the resulting matrix of cases studied.

The full set of 60 cases was initially evaluated for reliability using 100% CBS (Catalogue Break Strength) for the mooring line. The entire set of 60 was then re-evaluated using 80% CBS to determine the sensitivity of the results to lower than expected mooring line strength.

For the 8-10 mooring line cases, the first and second line failures were determined. The second line failure was used to represent the mooring system failure. For the 12 and 16 line cases, the third line failure was also determined, with the third line failure representing the mooring system failure. This allowed a comparison of the effect of mooring line redundancy in terms of the first line failure, versus the mooring system failure.

Table 1 – Full Set of Cases Studied

Case	MODU				Mooring System				No. of Lines			Water Depth			Metocean Zone			DRP			
	1	2	3	6	C	S	PI	PT	8-10	12	16	1,000'	3,000'	6,000'	C	WC	W	10	25	50	100
1	X				X				X				X		X			X			
2	X				X				X			X			X			X			
3				X	X				X				X		X			X			
4				X	X				X					X	X			X			
5				X		X			X					X	X			X			
6				X				X	X					X	X			X			
7				X			X		X					X	X			X			
8				X	X					X			X		X			X			
9				X				X		X				X	X			X			
10				X			X			X				X	X			X			
11				X	X						X		X		X			X			
12				X				X			X			X	X			X			
13		X			X				X				X		X			X			
14		X			X					X			X		X			X			
15			X		X				X				X		X			X			
16			X		X					X			X		X			X			
17		X						X		X				X	X			X			
18			X					X		X				X	X			X			
19		X					X			X				X	X				X		
20			X				X			X				X	X				X		
21	X				X				X				X			X			X		
22	X				X				X			X				X			X		
23				X	X				X				X			X			X		
24				X	X				X					X		X		X			
25				X		X			X					X		X		X			
26				X				X	X					X		X		X			
27				X			X		X					X	X				X		
28				X	X					X			X		X				X		
29				X				X		X				X	X				X		
30				X			X			X				X	X				X		
31				X	X						X		X		X				X		
32				X				X			X			X	X				X		
33		X			X				X				X			X			X		
34		X			X					X			X		X				X		
35			X		X				X				X			X			X		
36			X		X					X			X		X				X		
37		X						X		X				X	X				X		
38			X					X		X				X	X				X		
39		X					X			X				X	X					X	
40			X				X			X				X	X					X	
41	X				X				X				X			X				X	
42	X				X				X			X				X				X	
43				X	X				X				X				X		X		
44				X	X				X					X			X	X			
45				X		X			X					X			X	X			
46				X				X	X					X		X			X		
47				X			X		X					X		X			X		
48				X	X					X			X			X				X	
49				X				X		X				X		X				X	
50				X			X			X				X	X					X	
51				X	X						X		X		X					X	
52				X				X			X			X	X					X	
53		X			X				X				X			X				X	
54		X			X					X			X		X					X	
55			X		X				X				X			X				X	
56			X		X					X			X			X				X	
57		X						X		X				X	X					X	
58			X					X		X				X	X					X	
59		X					X			X				X	X						X
60			X				X			X				X	X						X

Notes:

1.MODU Class
- 1 = 30,000mt, 2nd or 3rd generation
- 2 = 35,000mt, 4th generation up-gradable
- 3 = 25,000mt, 4th generation up-gradable
- 6 = 45,000mt, 4th or 5th generation up-gradable

2.Mooring System
- C = Catenary
- S = Steel Semi-Taut
- PI = Polyester Insert
- PT = Polyester Taut

3.Metocean Zone
- C = Central
- WC = West Central
- W = West

4.DRP = Design Return Period

Analysis Methodology

The procedure for calculating the notional annualized probability of failure, as illustrated in Figure 1, contains the following six main steps:

1) Define random variables. The random variables generally follow Deepstar-4404 report [1]. The statistical distributions, which are listed in Table 2, have been reviewed in MODU JIP technical steering committee meetings as well as general participant meetings during the progression of the MODU JIP project.

2) Simulate random variables input. The Monte Carlo simulation software Crystal Ball [4] was used to generate the samples of the random variables (approximately 500 analyses for each of the 60 cases). The Monte Carlo simulation approach was adopted by the MODU JIP project rather than the first-order or second-order reliability approaches. The Monte Carlo simulation used is a condensed version of the traditional Monte Carlo simulation, in which the 500 simulations were used to generate the probabilistic distribution of ratios between mooring line tension to strength, and not used to determine the probability of failure. The probability of failure is described in Step 5.
3) Perform Mooring Analysis. Deterministic mooring analyses are conducted for all sets of random inputs. Detailed descriptions of deterministic analyses can be found in [7].
4) Record mooring line tensions. The top six most loaded line tensions for each case analyzed, including their mean, wave frequency and low frequency components, were recorded in an output data file.
5) Calculate annual probability of failure. Annual probability of failure was estimated by simulating line tension to line strength ratios. A fragility approach and system symmetry and direction weighting were also used in the annual probability of failure estimation.

The probability distributions for wind speed, wave height and current speed in reliability analysis were taken from MODU JIP Metocean report [5] with the given Weibull distribution parameters contained therein. The "Peak Wind with Associated Wave and Current Case" was used in reliability analysis. Figure 2 gives the wind speed distributions for 1-yr, 10-yr, 50-yr and 100-yr return period. These distributions represent maximum one-hour wind speeds for a large number of, say, 10-year return period events. The 1-year distribution represents the distribution of annual hurricane induced winds. Note that in Figure 2 the wind speed axis is normalized to the 10-yr wind speed. It is noted that the annual wind speed distribution as shown in Figure 2 was back-calculated from the N-yr distributions. The N-yr distributions were calculated from MODU JIP metocean study based on hurricane statistics. The back-calculated annual wind speed distribution is thus only approximate, particularly on the low-end tail. However, the high-end tail of the annual wind speed distribution, which is the most important part in annual probability of failure calculation, is relatively more accurate.

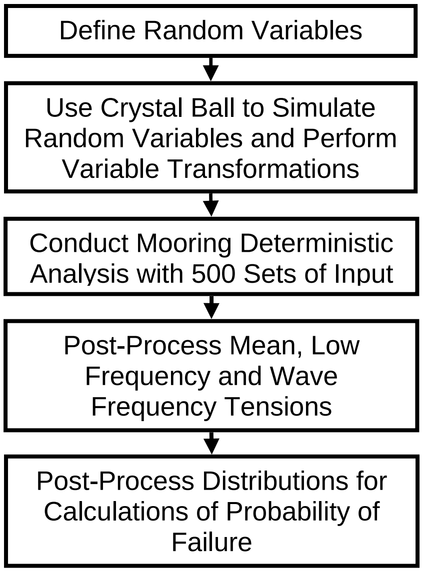


Figure 1 – Procedure of Reliability Analysis

The notional annual failure probability was calculated by the "fragility curve approach" as shown in Figure 3. The notional annual probability of failure is given as the following equation:

$$\text{Annual } p_f = \int_0^\infty f(x) \cdot A(x)dx, \qquad (1)$$

where f(x) is the 1-yr wind speed distribution as shown in Figure 2, A(x) is the conditional probability of failure (the fragility curve) as shown in Figure 3. The fragility curve was created by best fitting a Weibull distribution function through a data set of four points.

The data set of four conditional probabilities of failure were calculated based on tables such as shown in Figure 4, which contains some intermediate probability of failure results for an eight-line MODU with the mooring line arrangement as shown in Figure 5. Figure 6 contains the Monte Carlo simulation results for this example MODU. From these results the intermediate pfs in Figure 4 were filled and the conditional probabilities under 10-yr, 25-yr, 50-yr and 100-yr were calculated. These conditional pfs were then synthesized into annual pf by way of Eq.(1). Note that the hurricanes are considered to approach the MODU from 0-deg (see Figure 5) with 25% probability, from 45-deg with 50% probability and 90-deg with 25% probability. These directional combinations were used to finally come up with a single annual pf.

Table 2 - Random Variable Distributions and Parameters

No.	Random Variable	Symbol	Applied as	Distribution and Parameters*
1	Mean Tension	X_1	Factor	Lognormal, $\varepsilon = 0.8$, $\mu = 1.0$, $\sigma = 0.05$
2	Low Frequency Tension	X_2	Factor	Lognormal, $\varepsilon = 0.75$, $\mu = 1.0$, $\sigma = 0.075$
3	Wave Frequency Tension	X_3	Factor	Lognormal, $\varepsilon = 0.7$, $\mu = 1.0$, $\sigma = 0.10$
4	Wind Velocity	X_4	Factor	Weibull (max), see Table 4.2
5	Wind Direction	X_5	Additive	Normal, $\mu = 0$, $\sigma = 2.5$ (degrees)
6	Significant Wave Height	X_6	Factor	Weibull (max), see Table 4.2
7	Peak Period	X_7	Additive	Normal, $\mu = 0.0$, $\sigma = 0.55$ (seconds)
8	Gamma	X_8	Factor	Normal, $\mu = 1.0$, $\sigma = 0.15$
9	Wave Direction	X_8	Additive	Normal, $\mu = 0$, $\sigma = 10.0$ (degrees)
10	Current Velocity	X_{10}	Factor	Weibull (max), see Table 4.2
11	Current Direction	X_{11}	Additive	Normal, $\mu = 0$, $\sigma = 10.0$ (degrees)
12	Surge Damping	X_{12}	Factor	Normal, $\mu = 1.0$, $\sigma = 0.15$
13	Sway Damping	X_{13}	Factor	Normal, $\mu = 1.0$, $\sigma = 0.15$
14	Yaw Damping	X_{14}	Factor	Normal, $\mu = 1.0$, $\sigma = 0.15$
15	Heave Damping	X_{15}	Factor	Normal, $\mu = 1.0$, $\sigma = 0.15$
16	Roll Damping	X_{16}	Factor	Normal, $\mu = 1.0$, $\sigma = 0.15$
17	Pitch Damping	X_{17}	Factor	Normal, $\mu = 1.0$, $\sigma = 0.15$
18	Line Drag Coefficient	X_{18}	Factor	Normal, $\mu = 1.0$, $\sigma = 0.20$
19	Line Compliance	X_{19}	Factor	Normal, $\mu = 1.0$, $\sigma = 0.15$
20	Pretensions	X_{20}	Factor	Normal, $\mu = 1.0$, $\sigma = 0.06$
21	Wind Force Coefficient	X_{21}	Factor	Normal, $\mu = 1.0$, $\sigma = 0.06$
22	Current Force Coefficient	X_{22}	Factor	Normal, $\mu = 1.0$, $\sigma = 0.06$
23	Center of Effort	X_{23}	Additive	Normal, $\mu = 0.0$, $\sigma = 6.08$ (feet)
24	Capacity	X_{24}	Factor	Weibull (min), $\varepsilon = 0.4$, $\mu = 1.0$, $\sigma = 0.10$

Note: ε is the threshold, μ is the mean, and σ is the standard deviation.

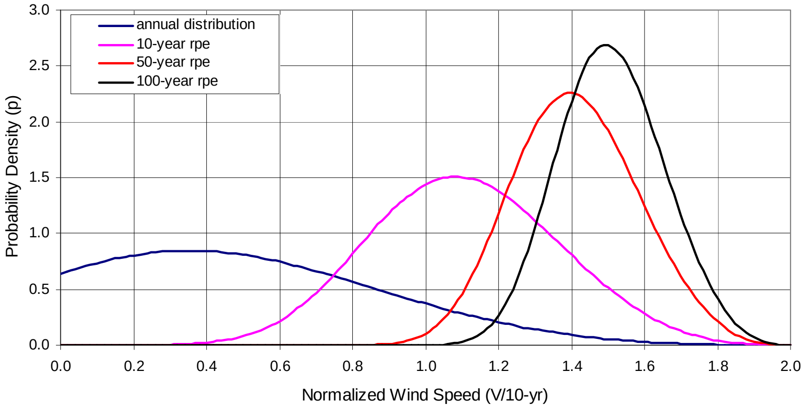


Figure 2 – Annual and N-year Return Period Distributions Wind Speed

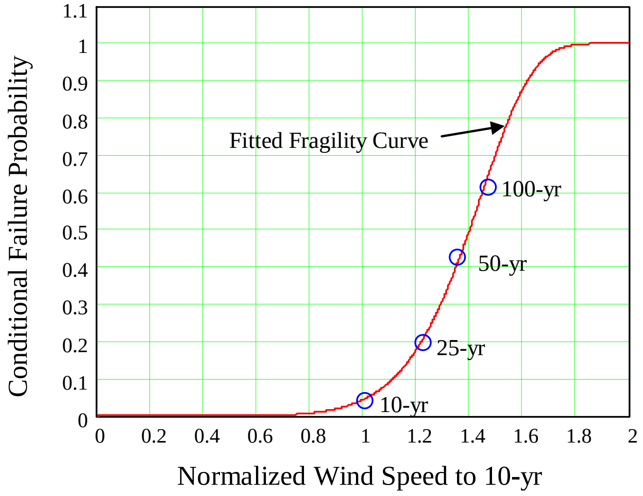
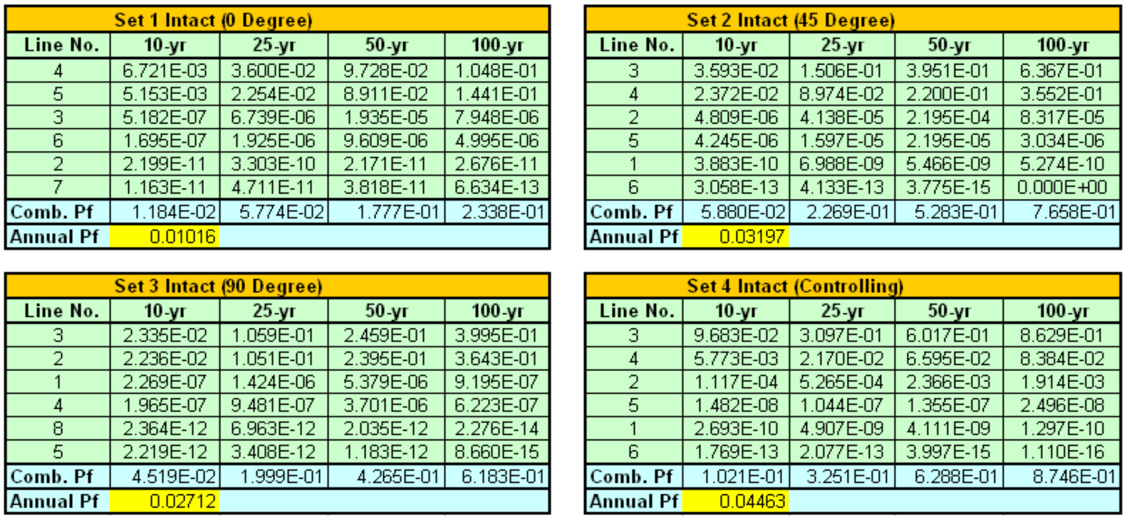


Figure 3 – Fragility Curve (Conditional Probability of Failure Given Occurrence of N-yr Hurricane)



Set 1 Intact (0 Degree)

Line No.	10-yr	25-yr	50-yr	100-yr
4	6.721E-03	3.600E-02	9.728E-02	1.048E-01
5	5.153E-03	2.254E-02	8.911E-02	1.441E-01
3	5.182E-07	6.739E-06	1.935E-05	7.948E-06
6	1.695E-07	1.925E-06	9.609E-06	4.995E-06
2	2.199E-11	3.303E-10	2.171E-11	2.676E-11
7	1.163E-11	4.711E-11	3.818E-11	6.634E-13
Comb. Pf	1.184E-02	5.774E-02	1.777E-01	2.338E-01
Annual Pf	0.01016			

Set 2 Intact (45 Degree)

Line No.	10-yr	25-yr	50-yr	100-yr
3	3.593E-02	1.506E-01	3.951E-01	6.367E-01
4	2.372E-02	8.974E-02	2.200E-01	3.552E-01
2	4.809E-06	4.138E-05	2.195E-04	8.317E-05
5	4.245E-06	1.597E-05	2.195E-05	3.034E-06
1	3.883E-10	6.988E-09	5.466E-09	5.274E-10
6	3.058E-13	4.133E-13	3.775E-15	0.000E+00
Comb. Pf	5.880E-02	2.269E-01	5.283E-01	7.658E-01
Annual Pf	0.03197			

Set 3 Intact (90 Degree)

Line No.	10-yr	25-yr	50-yr	100-yr
3	2.335E-02	1.059E-01	2.459E-01	3.995E-01
2	2.236E-02	1.051E-01	2.395E-01	3.643E-01
1	2.269E-07	1.424E-06	5.379E-06	9.195E-07
4	1.965E-07	9.481E-07	3.701E-06	6.223E-07
8	2.364E-12	6.963E-12	2.035E-12	2.276E-14
5	2.219E-12	3.408E-12	1.183E-12	8.660E-15
Comb. Pf	4.519E-02	1.999E-01	4.265E-01	6.183E-01
Annual Pf	0.02712			

Set 4 Intact (Controlling)

Line No.	10-yr	25-yr	50-yr	100-yr
3	9.683E-02	3.097E-01	6.017E-01	8.629E-01
4	5.773E-03	2.170E-02	6.595E-02	8.384E-02
2	1.117E-04	5.265E-04	2.366E-03	1.914E-03
5	1.482E-08	1.044E-07	1.355E-07	2.496E-08
1	2.693E-10	4.907E-09	4.111E-09	1.297E-10
6	1.769E-13	2.077E-13	3.997E-15	1.110E-16
Comb. Pf	1.021E-01	3.251E-01	6.288E-01	8.746E-01
Annual Pf	0.04463			

Figure 4 – Example Results of an Eight-Line Mooring System

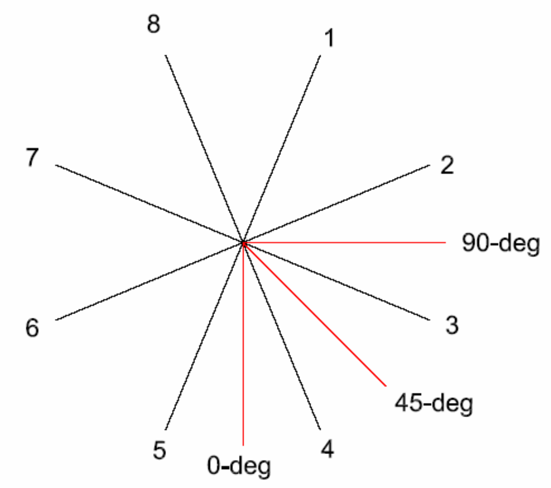


Figure 5 – Schematics of an Eight-Line Mooring System

Note that in Figure 4, a 4th direction of "Controlling" direction is also considered. This is the direction from which the MODU mooring lines are most vulnerable. This controlling direction is only for reference purpose and is not involved in the overall annual pf calculations.

The methodology of how to calculate the annual probability of failure of *one line* in a mooring system is presented previously. In this study, for an eight-line system (or base system), the system is considered to have failed as two lines or more fail, while for a 12- or 16-line system, the system is considered to have failed when three lines or more fail. Therefore, the probability of *the mooring system failure* can be defined as the probability of two-line or three-line failure in the system, depending on how many mooring lines the system has.

In this project, we assume that the event of a mooring system failure is a sequence of individual line failures. For example, for an eight-line system failure, the event of system failure is that first any line fails and then any remaining second line fails. Though differences exist between one-line failure and system failure, the procedure of calculating the annual probability of failure, namely the fragility approach as demonstrated in the previous subsection, can also be applied to calculate the annual probability of system failure.

Figures 4 and 5 are used again for the system pf calculations. As mentioned previously, the event of a mooring system failure is a sequence of individual line failures. To obtain the probability of system failure, the probability of one mooring line failure, denoted as P_{intact}, is first calculated. And then the probability of *any second* line failure, denoted as $P_{damaged}$, is calculated. In order to cover all the eight lines in all directions, three sets of simulations are performed for 0°, 45°, and 90° load directions, respectively. Taking the example of the "Set 1" table in Figure 4, the system failure for this direction (0 degree) for any return period event is written as

$$P_{0\text{-}deg} = \{P_{damaged,line4} \bigcap P_{intact,line4}\} \bigcup \{P_{damaged,line5} \bigcap P_{intact,line5}\}, \qquad (2)$$

in which the symbol “$\bigcup$” is the union operator between probabilistic events, and “$\bigcap$” is the intersecting operator between probabilistic events. $P_{damaged,\ line\ 4}$ is the combined probability of any remaining line failure after line 4 was broken; similarly $P_{damaged,\ line\ 5}$ is the combined probability of any remaining line failure after line 5 was already broken. The same directional combination rule among 0°, 45°, and 90° applies in order to obtain the annual pf for mooring system failures.

The same logic can be applied to obtain the mooring system failure for 12 and 16-line systems. For these two systems, a failure of three lines is considered to consititue system failure.

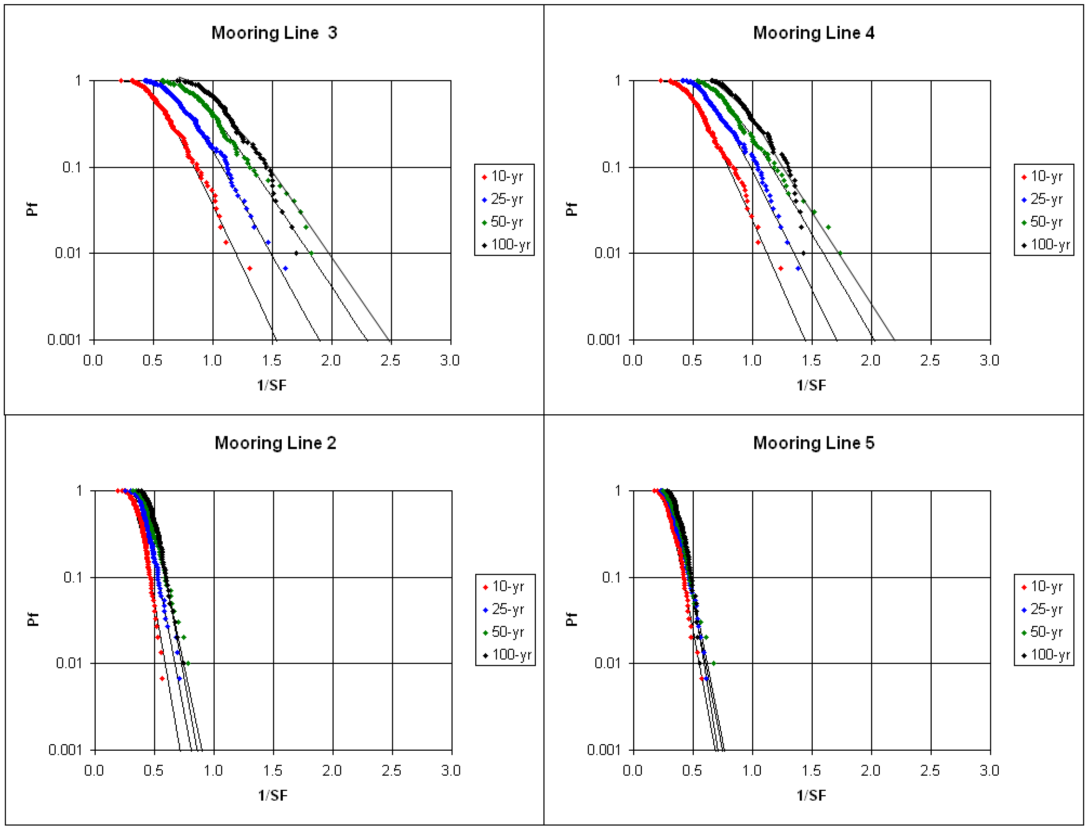


Figure 6 – pf vs. 1/SF for each mooring line (Case 1, Set 2)

MODU Reliability Results and Comparisons

The range of cases studied is presented in Table 3, which is color coded by the Gulf of Mexico metocean zone and base design return period. Below the table is a key to the color coding along with the range of calculated notional probabilities of system failure for that particular design case. Detailed results for each case are contained within the confidential JIP Reliability report [8]. The Central region is presented in orange color with different shades, while the West Central in blue color and the West region in green color, also with different shades. The shade differences are used to denote the design return periods. For example, for the Central region all MODUs with 10-yr design are colored with dark orange, and the shades are increasingly lighter for the 25, 50 and 100-yr design return periods. As indicated previously, the results represent notional reliabilities that demonstrate the relative reliabilities.

All cases are calculated with the 1-line, 2-line and (where applicable) 3-line failure scenarios. For the base design cases (8, 9 or 10-line configurations), the failure of 2 lines constitutes the system failure. For 12-line and 16-line configurations, 3-line failure is considered as system failure and in these cases the 3-line failure results were calculated. The overall results are also illustrated with three-dimensional bar plots, as shown in Figure 7 using the same color code.

Among all 60 analysis cases, 40 cases are central region, 17 cases are west central region and 3 cases are west region. Central region cases cover different return period designs varying from 10yr to 100yr, and different number of mooring lines (8 to 10 lines, 12 lines, and 16 lines). West central region cases include 10-yr, 25-yr, 50-yr designs as well as base and 12-line systems. Only three run cases with basic design belong to west region.

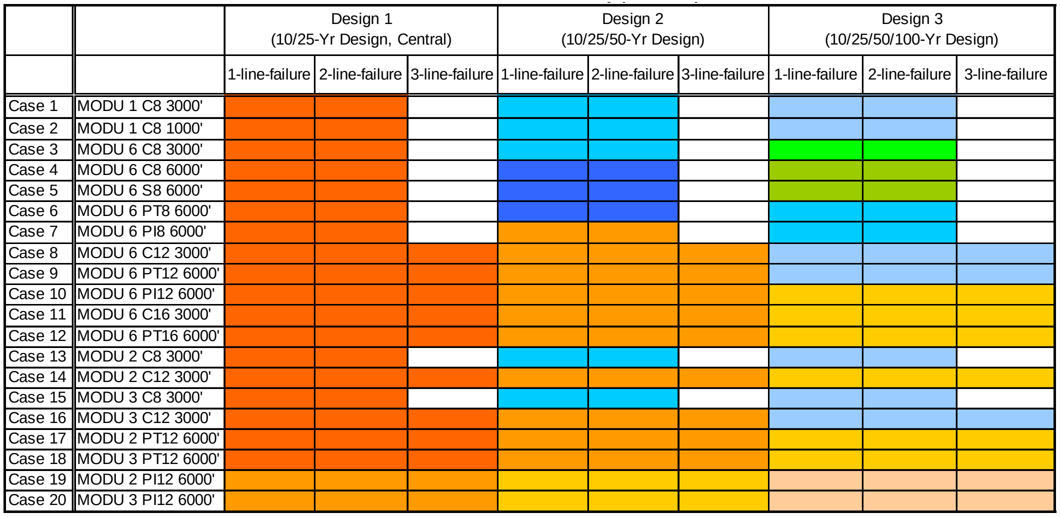
Reliability Comparison Between Different Design Return Periods

As the design return period increases, the MODU mooring system has higher capacity and it can be expected that the MODU failure probability in an annual extreme metocean event will decrease (i.e. higher design return period gives a lower annual probability of failure). It is observed that:

- By increasing the design return period from 10-yr to 25-yr, the annual pf is reduced approximately by a factor of 5.

- By increasing the design return period from 10-yr to 50-yr, the annual pf is reduced approximately by one order of magnitude.
- By increasing the design return period from 10-yr to 100-yr, the annual pf is reduced approximately by two orders of magnitude.

Table 3 - All Studied Scenarios and Probability of Failure Summary (100% CBS)



		Design 1 (10/25-Yr Design, Central)			Design 2 (10/25/50-Yr Design)			Design 3 (10/25/50/100-Yr Design)		
		1-line-failure	2-line-failure	3-line-failure	1-line-failure	2-line-failure	3-line-failure	1-line-failure	2-line-failure	3-line-failure
Case 1	MODU 1 C8 3000'	🟥	🟥		🔵	🔵		🔹	🔹	
Case 2	MODU 1 C8 1000'	🟥	🟥		🔵	🔵		🔹	🔹	
Case 3	MODU 6 C8 3000'	🟥	🟥		🔵	🔵		🟩	🟩	
Case 4	MODU 6 C8 6000'	🟥	🟥		🟦	🟦		🟢	🟢	
Case 5	MODU 6 S8 6000'	🟥	🟥		🟦	🟦		🟢	🟢	
Case 6	MODU 6 PT8 6000'	🟥	🟥		🟦	🟦		🔵	🔵	
Case 7	MODU 6 PI8 6000'	🟥	🟥		🟧	🟧		🔵	🔵	
Case 8	MODU 6 C12 3000'	🟥	🟥	🟥	🟧	🟧	🟧	🔹	🔹	🔹
Case 9	MODU 6 PT12 6000'	🟥	🟥	🟥	🟧	🟧	🟧	🔹	🔹	🔹
Case 10	MODU 6 PI12 6000'	🟥	🟥	🟥	🟧	🟧	🟧	🟨	🟨	🟨
Case 11	MODU 6 C16 3000'	🟥	🟥	🟥	🟧	🟧	🟧	🟨	🟨	🟨
Case 12	MODU 6 PT16 6000'	🟥	🟥	🟥	🟧	🟧	🟧	🟨	🟨	🟨
Case 13	MODU 2 C8 3000'	🟥	🟥		🔵	🔵		🔹	🔹	
Case 14	MODU 2 C12 3000'	🟥	🟥	🟥	🟧	🟧	🟧	🟨	🟨	🟨
Case 15	MODU 3 C8 3000'	🟥	🟥		🔵	🔵		🔹	🔹	
Case 16	MODU 3 C12 3000'	🟥	🟥	🟥	🟧	🟧	🟧	🔹	🔹	🔹
Case 17	MODU 2 PT12 6000'	🟥	🟥	🟥	🟧	🟧	🟧	🟨	🟨	🟨
Case 18	MODU 3 PT12 6000'	🟥	🟥	🟥	🟧	🟧	🟧	🟨	🟨	🟨
Case 19	MODU 2 PI12 6000'	🟧	🟧	🟧	🟨	🟨	🟨	🟫	🟫	🟫
Case 20	MODU 3 PI12 6000'	🟧	🟧	🟧	🟨	🟨	🟨	🟫	🟫	🟫

MODU 1 - 30,000mt
MODU 2 - 35,000mt
MODU 3 - 25,000mt
MODU 6 - 45,000mt

🟥	Central Region, 10-Year Design	pf range 0.021 - 0.095
🟧	Central Region, 25-Year Design	pf range 0.003 - 0.014
🟨	Central Region, 50-Year Design	pf range 0.001 - 0.006
🟫	Central Region, 100-Year Design	pf range 0.00006 - 0.00027
🟦	West Central Region, 10-Year Design	pf range 0.056 - 0.095
🔵	West Central Region, 25-Year Design	pf range 0.011 - 0.036
🔹	West Central Region, 50-Year Design	pf range 0.003 - 0.016
🟢	West Region, 10-Year Design	pf range 0.066 - 0.109
🟩	West Region, 25-Year Design	pf range 0.022 - 0.029

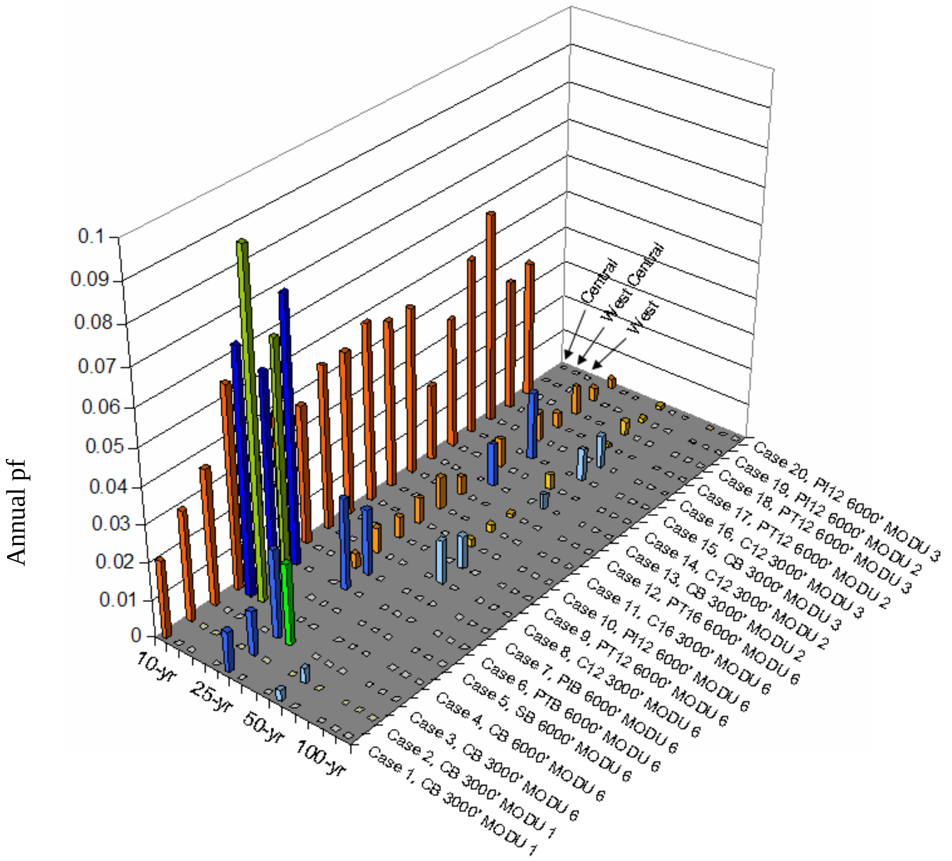


Figure 7 – Overall Results Summary Plot (100% CBS)

The trend plot for the Central Region is shown in Figure 8, similar trends have been observed for the West and West Central Regions.

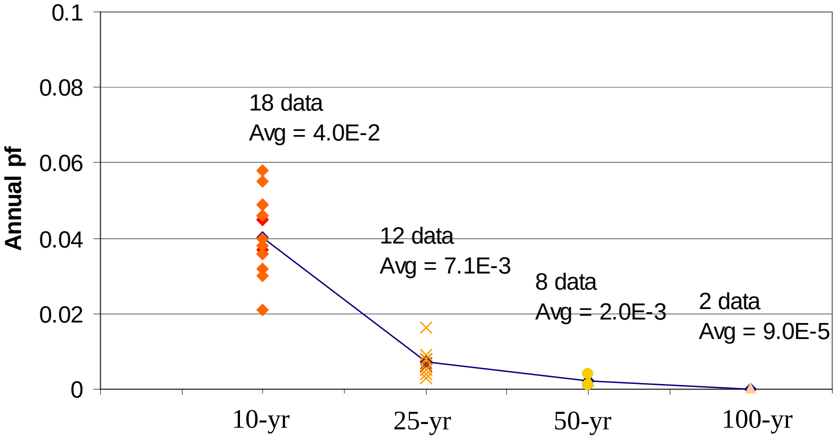


Figure 8 – Annual pf vs. Design Return Periods (Central Region)

Reliability Comparison Between 100% and 80% CBS

The entire set of annual failure probabilities was re-calculated with the mooring line strength assumed at 80% CBS. The reason 80% of CBS was chosen is that it could be argued that while in service mooring line may be only as effective as 80% of CBS: a 10% reduction breaking strength is allowed within API RP 2I, and a further 10% reduction in strength could occur due to bending over a fairlead. The intent is not to state that 80% is the actual effective break strength, but to determine the sensitivity to changes and possible component degradation while in service. On average, if the mooring strength is degraded from 100% CBS to 80% CBS, the following trends are observed:

- Annual p_f increases approximately 2 to 3 times for 10-yr design
- Annual p_f increases approximately 3 to 4 times for 25-yr design
- Annual p_f increases approximately 5 to 7 times for 50-yr design
- Annual p_f increases approximately more than 10 times for 100-yr design

The increased sensitivity with respect to higher return period designs can be explained in Figure 9, in which the ratios of mooring line tension to strength (i.e., 1/SF) are shown for typical 10-yr and 25-yr designs. The 10-yr design curve passes the 1.0 ratio (representing the failure point for 100% CBS) at 50-yr metocean event, and passes the 0.8 ratio (representing the failure point for 80% CBS) at 20-yr metocean event. Conceptually the annual failure probability (pf) can be thought of as the inverse of the metocean return period at failure point, thus for the 10-yr design curve an annual pf ratio of 2.5 (50 yr/20 yr) can be expected between the 100% CBS and 80% CBS cases. Similarly, the 25-yr return period design curve passes the 1.0 ratio at 400-yr metocean event and passes the 0.8 ratio at 100-yr metocean event. An annual pf ratio of 4.0 (400 yr/100 yr) can be expected between the 100% CBS and 80% CBS cases.

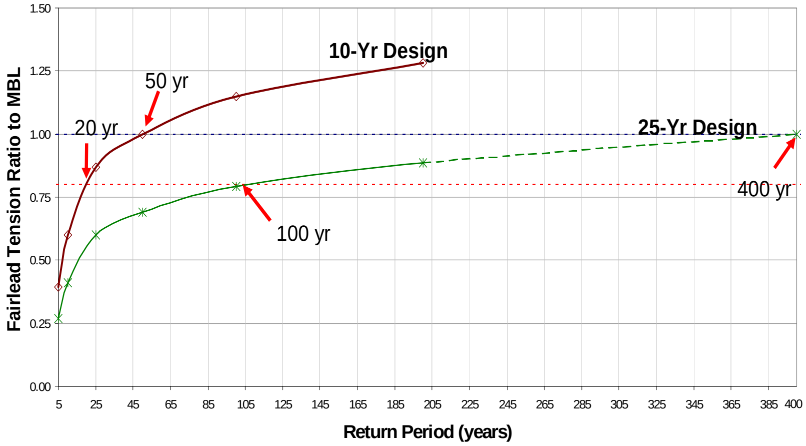


Figure 9 – Illustration of Increased Mooring Strength Sensitivity for Higher RP Designs (Case 18 Central 10 and 25-yr Designs)

The observation suggests that the condition of a mooring system is increasingly important as the design return period increases. A mooring system designed to a 10-year return period will not have a much larger probability of failure if it is found to be slightly below grade, or in imperfect condition. However, the effect of condition on the probability of failure of a mooring system designed to 100-year criteria will be much greater. There will always be a decrease in the probability of failure if the design is to a higher return period, but the magnitude of that decrease will be affected by the ratio of the actual mooring line break strength to its assumed break strength.

Reliability Comparison between Different Metocean Regions

Figure 10 presents the averaged pf for different return period designs and different GoM metocean regions. It is seen that for the same return period design, the probability of failure increases as the metocean region changes from Central to West Central to West region. It should be noted that a MODU that satisfies the 10-yr design criteria in the Central region might satisfy the 20-yr design criteria in the West Central region, and even higher design criteria in the West region. This has NOT been the basis for this comparison. The comparisons done in this subsection were done on the same design return period regardless of the region (e.g. all to 10-yr designs). In this sense a MODU mooring system has to be downgraded moving from Central region to the West and West Central regions to just meet the same 10-yr design criteria.

The main reason for the differences in annual pf is from the wind speed slope effects between different metocean zones. This is illustrated in Figure 11, in which the upper figure shows the absolute values of the 1-hour wind speed and the lower figure shows the wind speed values normalized to the 10-yr event. The West region has the highest slope as compared to other regions, and West Central slope is slightly higher than the Central region, as can be seen from Figure 11.

This conclusion is important when determining the relative reliability set by the API RP 2SK standard. The reliability established by that standard will vary depending where one is operating in the GoM: for the same design return period, a unit operating in the central Gulf will have a lower probability of failure than a unit operating in the western Gulf. While it is not anticipated that the required mooring line safety factors will be changed for the different areas of the Gulf, it is worth noting that a minimum design return period in the western Gulf will result in a higher probability of failure. Fortunately, the extremes in the western Gulf are lower than in the central Gulf, so a MODU having the same mooring system will be capable of a higher return period in the western Gulf. This increased return period capability will more than offset the increased probability of failure due to slope of the metocean extremes.

In general, it was found that from the reliability point of view, a 10-yr Central design will roughly correspond (with the same pf) to a 20-yr West Central design, and a 25-yr Central design will roughly correspond to a 50-yr West Central design. From West Central to West the designs are comparable (i.e. they have the same pf) although some slight differences exist. It is noted that the sample points for the West Central and West regions are not enough, as compared to the Central region, to draw a definitive quantitative conclusion at this time.

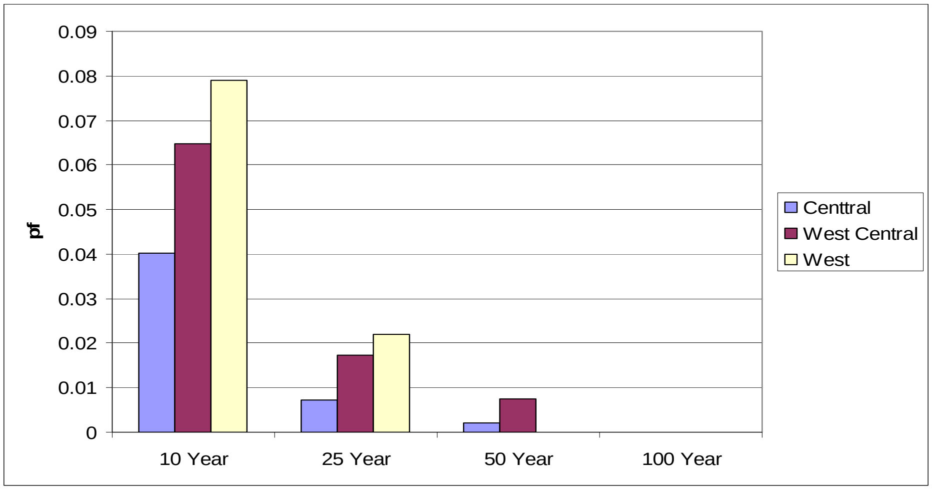


Figure 10 - Metocean Condition Effects on Averaged pfs for Different Return Period Designs (100% CBS case)

Effects of Number of Mooring Lines

Figure 12 gives the probability of failure for 3 mooring systems on the same MODU: a base case, a first upgrade to 12 mooring lines and a second upgrade to 16 mooring lines. It can be seen that for the actual systems that would be installed on a MODU the probability of failure decreases by more than an order of magnitude between the base case and the second (16 mooring line) upgrade.

A measure of redundancy for mooring system can be defined as follows:

$$Redundancy = 1 - (System\ pf / 1^{st}\ Line\ pf) \qquad (3)$$

If a mooring system fails right after the first line failure, this mooring system will have a zero redundancy based on the above definition. When assessing the redundancy of all the cases studied, it was realized that there was a significant spread over all of the cases. Consequently, the results for the base case and 12 line systems are likely to accurately reflect the real system redundancy. However, there were a limited number of 16 line cases assessed, and based on the results spread, it is possible that the 16 line system redundancy is greater than reported below. Based on all the simulated results, the averaged redundancies are as follows:

- 25% redundancy for the Base System
- 40% redundancy for the 12-Line System
- 45% redundancy for the 16-Line System

The above values are based on the use of 100% CBS. The redundancy does not appear to significantly change when assessed using the 80% CBS results.

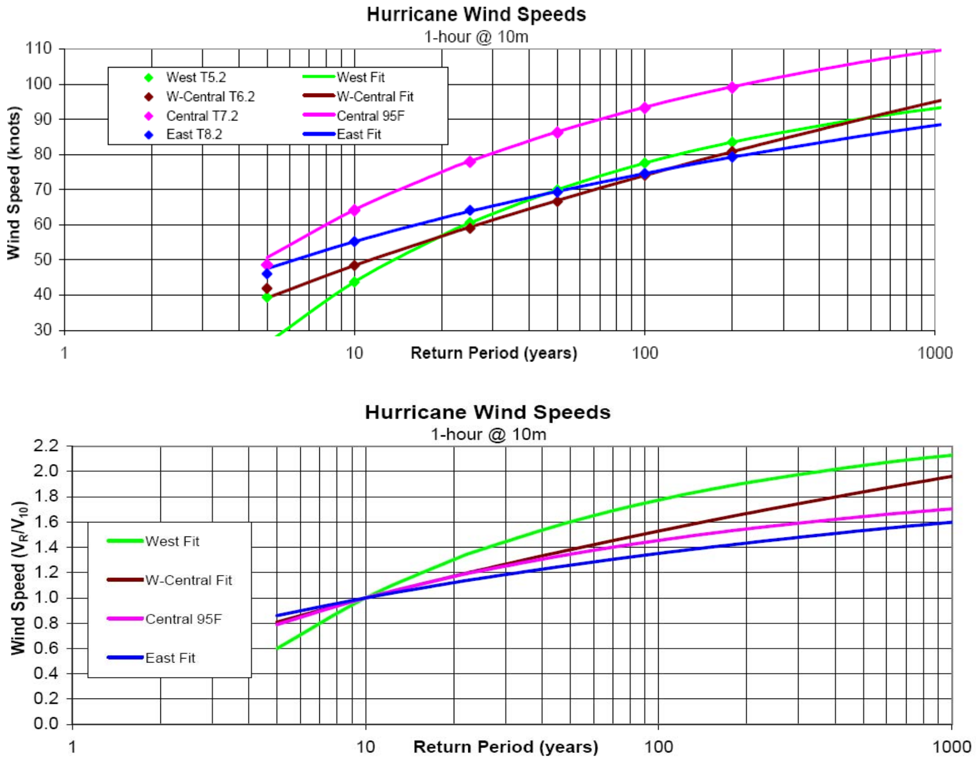


Figure 11 – 1-Hour Wind Speed in Four GoM Metocean Zones and Their Relative Slopes

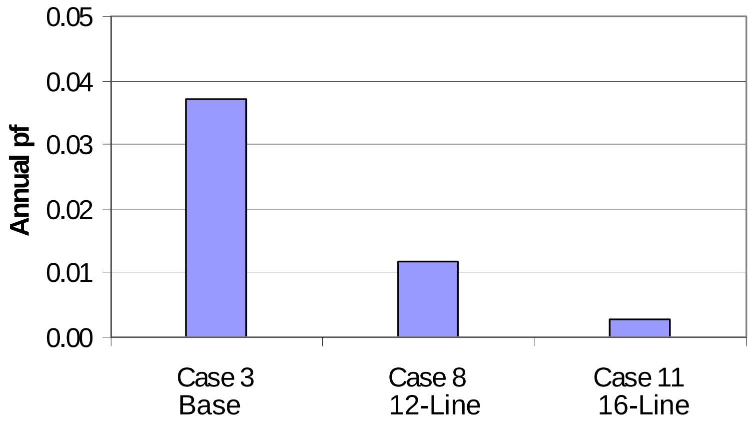


Figure 12 – Annual pf Comparison Between 8, 12 and 16-Line Systems, Original Designs

Comparisons of MODU Type and Water Depth

In the limited number of studied cases the differences are small among the mooring systems (catenary, steel, polyester insert and polyester taut). While there are some differences in system reliability, they are generally not significant.

On the effects of water depth, no firm conclusions can be drawn at this time based on the few comparison cases studied. However, the trend does not appear to be significant within the ranges considered.

Disclaimer

This paper was written based on work undertaken for the MODU Mooring Strength and Reliability Joint Industry Project, the results of which are subject to a confidentiality agreement. In a ballot, per the JIP participation agreement, the JIP participants agreed to the publication of this paper and any contained information. Notwithstanding this agreement, the views and conclusions contained in this paper are those of the authors and do not necessarily represent the views of any JIP participants or project team.

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