Report

Experience that Delivers

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Prepared for: BOEMRE

BOEMRE TA&R Program on Safety Oil and Gas Operations in the US OCS:

Ocean Current Monitoring from 500-1,000 Meters

June 2011

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Client: **BOEMRE**	BOEMRE
Project Name: **BOEMRE TA&R Program on Safety of Oil and Gas Operations in the US OCS**	
Document Title: **Ocean Current Monitoring from 500-1,000 Meters**	
Document Number: PR-10-1106	**Document Type:** Report
Client Document Number: Tax ID # 760597881 DUNS # 126065205 Sollicitation # M10PS00185	**Number of pages:** 56

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Rev	Date	Reason for Issue	Prep. By	Chk. By	App. By	QA	Client Approval
02	15 Aug 2011	Issued for BOEMRE Review	RP/KS	BO	AE		
01	23 June 2011	Issued for BOEMRE Review	RP/KS	BO	AE		

COMMENTS SHEET		
REVISION	**DATE**	**COMMENTS**
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1.0 EXECUTIVE SUMMARY

This study is part of the TA&R program of the Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE) of the U.S. Department of the Interior. The contract was awarded to MCS Kenny and Fugro GEOS, and the work was performed by scientists and engineers from MCS Kenny (Ayman Eltaher, Program Manager, Dr. Burak Ozturk, Project Lead and Kartik Sharma, Senior Specialist) and Fugro (Shejun Fan, Fugro Project Lead, Lie-Yauw Oey, Scientist at Princeton University and Fugro Consultant and Liam Harrington-Missin, Senior Oceanographer).

The objectives of the study are to:

1. Assess the characteristics of Gulf of Mexico current forcing in the 500 to 1,000 meter range and occurrence of elevated events; and
2. Use those data to assess the importance of such currents on the fatigue and design of risers, moorings and TLP tendons.

The first objective is addressed in the separate report by Fugro GEOS, which describes how BOEMRE's NTL ADCP data, historical mooring current data and Princeton University's PROFS model data were used to derive the current profiles to be used in addressing the second objective. In particular, Based on the analysis of current characteristics, ocean current kinetic energy distribution and observational data availability, four representative zones are indentified and addressed as consistent units and current characteristics. Zone 1 and 3 are areas dominated by Loop Current/Loop Current Eddie events and hurricane generated currents; zone 2 is an area with relatively strong currents found near the continental rise and slope in the northern Gulf especially where isobaths converge or narrow; and zone 4 is the new front area and corresponding to the high kinetic energy at 500 m. The study concluded that most of the events are within the top 500m, only a few weak deep (deeper than 500 m) events were identified. Nevertheless, long term and extreme events full water column current profile characterizations (representative current profiles and associated probabilities) were derived for each zone and provided for the use in the subsequent riser analysis.

This document addresses the second objective and the riser VIV fatigue analysis performed by MCS Kenny. In particular, the current profiles provided by Fugro GEOS were to be used in determining whether monitoring ocean current between 500 and 1,000 m should be required and used in assessing VIV fatigue damage of risers (Drilling, SCR, TTR, and Hybrid) and TLP tendons in the GoM.

The fatigue can be defined as the progressive and localized structural damage that occurs within a material under repeated cyclic loading. Fatigue life is defined as the service life of a component (riser in our case) before it is deemed unacceptable for any further service life, because of the accumulated fatigue damage.

The methodology to achieve this objective was to compare the VIV fatigue damage calculated based on the following current characteristics between 500 and 1,000 m:

1. Current profile typically assumed by designers with the lack of actual recorded profiles, which is generally an extension of the current velocity at 500 m, dubbed a linear current.
2. Current profiles, as monitored and provided by Fugro GEOS.

Depending on the relative values of the VIV damage resulting from either current profiles, conclusion can be drawn as to the importance of monitoring and using current data between 500 and 1,000 m in assessing VIV damage of risers and tendons in the GoM.

Due to the different parameters involved in the study (current parameters/zone, riser types, water depth, etc.), considering all possible combinations of those parameters to obtain a comprehensive conclusion is deemed impractical. To optimize the number of cases considered for actual analysis, the combinations of parameters in those cases were determined as follows:

3. A sensitivity study was performed, and a conclusion was drawn that water depth is not a governing factor; so the water depth of 4,000 m was selected for consideration in subsequent analyses.
4. A sensitivity study was performed and the TTR and hybrid riser were found to experience the largest difference in damage when the existing and actually recorded current profiles were assumed. Therefore, the two types of risers were selected for consideration in subsequent analyses.
5. No elevated current events were found in the metocean data of Zone 4. Therefore, and based on the above considerations, all possible combinations of the water depth (of 4,000 m), riser types (of TTR and hybrid risers), and Zones 1, 2 and 3 were considered in the VIV fatigue analyses.

MCS Kenny has the following opinion based on the results of the performed detailed VIV analyses:

6. The difference between fatigue life estimates based on the two (existing & new) profiles of long-term current events is not significant. Therefore, monitoring of long term current events between water depths of 500 - 1,000 m is not needed;
7. The difference between fatigue life estimates based on the two (existing & new) profiles of short-term current events is also not needed, if the probabilistic distribution of extreme current events is utilized for calculating the riser fatigue life;
8. The difference between fatigue life estimates based on the two (existing & new) is observed for the extreme events, if a single current event is utilized to obtain the fatigue life estimation, as shown in Appendices. The single extreme current event assumption is nonetheless particularly conservative and should be avoided.

Results of the analyses and MCS Kenny's opinion, based on the results, are documented in this report for BOEMRE to assess and conclude regarding the significance of the difference between the VIV fatigue damage under either of the current profiles, and consequently, on the requirement regarding monitoring of the current between 500 and 1,000 meters in the GoM.

2.0 INTRODUCTION

2.1 Project Description

The Ocean Current Monitoring from 500 - 1,000 meters study is part of the TA&R program of the Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE) of the U.S. Department of the Interior, with the objectives being to:

9. Assess the characteristics of Gulf of Mexico current forcing in the 500 to 1,000 meter range and occurrence of elevated events; and
10. Use those data to assess the importance of such currents on the fatigue and design of risers, moorings and TLP tendons.

The study was conducted as collaboration between MCS Kenny and Fugro GEOS, where the first objective was addressed in the separate report by Fugro GEOS [Ref 2]. The second objective is the subject of this report and was undertaken by MCS Kenny.

Ref [2] describes how BOEMRE's NTL ADCP data, historical mooring current data and Princeton University's PROFS model data were used to derive the current profiles to be used in the riser/Tension Leg Platform (TLP) tendon Vortex Induced Vibration (VIV) fatigue study described in this report. In particular, Based on the analysis of current characteristics, ocean current kinetic energy distribution and observational data availability, four representative zones are indentified and addressed as consistent units and current characteristics. Zone 1 and 3 are areas dominated by Loop Current/Loop Current Eddie events and hurricane generated currents; zone 2 is an area with relatively strong currents found near the continental rise and slope in the northern Gulf especially where isobaths converge or narrow; and zone 4 is the new front area and corresponding to the high kinetic energy at 500 m. The study concluded that most of the events are within the top 500 m, only a few weak deep (deeper than 500 m) events were identified. Nevertheless, long term and extreme events full water column current profile characterizations (representative current profiles and associated probabilities) were derived for each zone and provided for the use in this riser VIV fatigue study.

This document addresses the second objective. In particular, the current profiles provided by Fugro GEOS are to be used in determining whether monitoring ocean current between 500 and 1,000 m should be required and used in assessing VIV fatigue damage of the following types of structure, in the Gulf of Mexico (GoM):

1. Drilling Risers;
2. Steel Catenary Risers (SCR's);
3. Top Tension Risers (TTR's);
4. Hybrid Risers; and
5. TLP tendons

The following sections of the report describe the methodologies used in collecting and interpreting ocean current data and in using that data in the riser/tendon VIV fatigue analysis work and interpreting the results; and final conclusions and recommendations.

2.2 Scope of the Document

All the relevant design information regarding the models, analysis methodology, and the results based on the study forms the content of this document.

2.3 Analysis Software

Details of the software used in the analyses performed in this study are presented in Table 2-1.

Table 2-1: Software Used in the Study

Software	Description
Flexcom	Time domain non-linear FE software for strength & fatigue Analysis.
Modes	A Flexcom additional module. Modes calculates natural frequencies and mode shapes of offshore structures.
Shear7	A finite element eigensolution software for VIV analysis

2.4 Systems of Units

All data within this document are presented in the US Customary units system.

2.5 Abbreviations

The following abbreviations are used in this document.

ADCP Acoustic Doppler Current Profiler

Amax/D Maximum Amplitude over Diameter

API American Petroleum Standard

ASTM American Society for Testing and Materials

BHP Bottom Hole Pressure

BOP	Blowout Preventer
DNV	Det Norske Veritas
FE	Finite Element
FSHR	Free Standing Hybrid Riser
GoM	Gulf of Mexico
HRS	Hybrid Riser System
ISO	International Standards Organization
LCE	Loop Current Eddy
LMU	Load Measuring Unit
NDBC	National Data Buoy Center
NTL	Notice to Lessees and Operators
OD	Outer Diameter
PROFS	Princeton Regional Ocean Forecasting System
SCF	Stress Concentration Factor
SCR	Steel Catenary Riser
S-N	Stress vs. Number of Cycles to Failure
TDP	Touch Down Point
TLP	Tension Leg Platform
TLP-T	Tension Leg Platform - Tendon
TRW	Topographic Rossby Waves
TTC	Tendon Top Connector
TTR	Top Tension Riser
VIV	Vortex Induced Vibration

3.0 METHODOLOGY

3.1 Selection of Gulf of Mexico Zones

3.1.1 General

To optimize data management and analyses, Fugro and Princeton provided selected representative Zones of the GoM so that the analysis could be performed on risers or tendon systems which can provide a realistic response of the impact of increased current monitoring depth on calculated riser or tendon system VIV fatigue damage.

The selection of representative study areas are based on current characteristics, ocean current kinetic energy distribution and observational data availability.

This section provides summary of current characteristics that were studied in four (4) zones in the GoM.

3.1.2 Current Characteristics

There are four known processes that can generate strong currents in the deepwater GoM:

- Currents caused by energetic atmospheric events including inertial oscillations driven by hurricanes.
- Surface-intensified circulation features including the Loop Current and associated eddies.
- Deep barotropic currents including topographic Rossby waves and associated near bed flows.
- High-speed subsurface-intensified currents.

Figure 3-1 shows all category 4 and 5 historical hurricane tracks that in the GoM. Hurricanes are fairly uniformly distributed in the oil-producing regions of the northern GoM. Fast moving hurricanes usually excite large inertial currents. With existing strong anticyclone Loop Current Eddy (LCE), the inertial currents can penetrate into the deep portions of the LCE. These deep penetrations and trapping of inertial energy occur days (up to ~ 10) after the hurricane passed, and can have important implications to the riser systems.

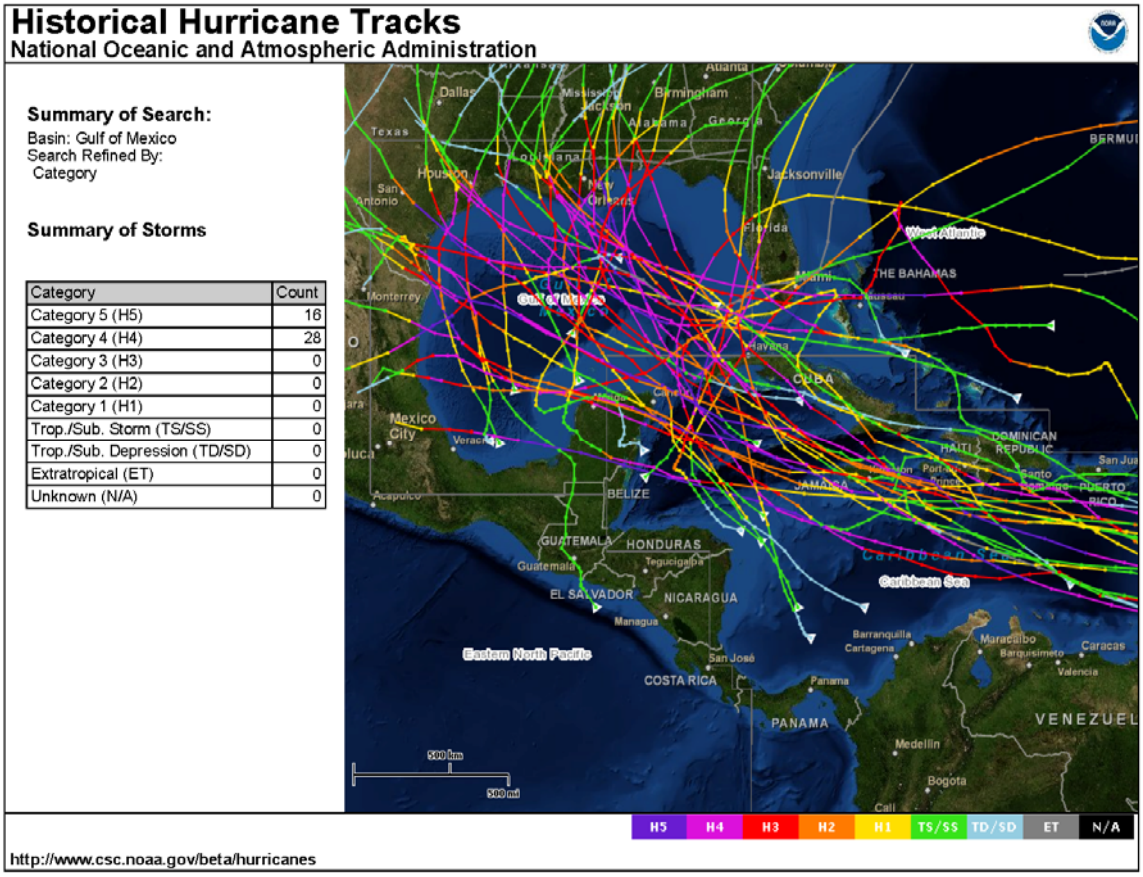

Figure 3-1: Historical Category 4 and 5 Hurricanes in the GoM

Figure 3-2 is measured wind/wave/pressure and current data during hurricane Katrina. The inertial energy penetrated as deep as 1,000 m thanks to the existence of eddy vortex.

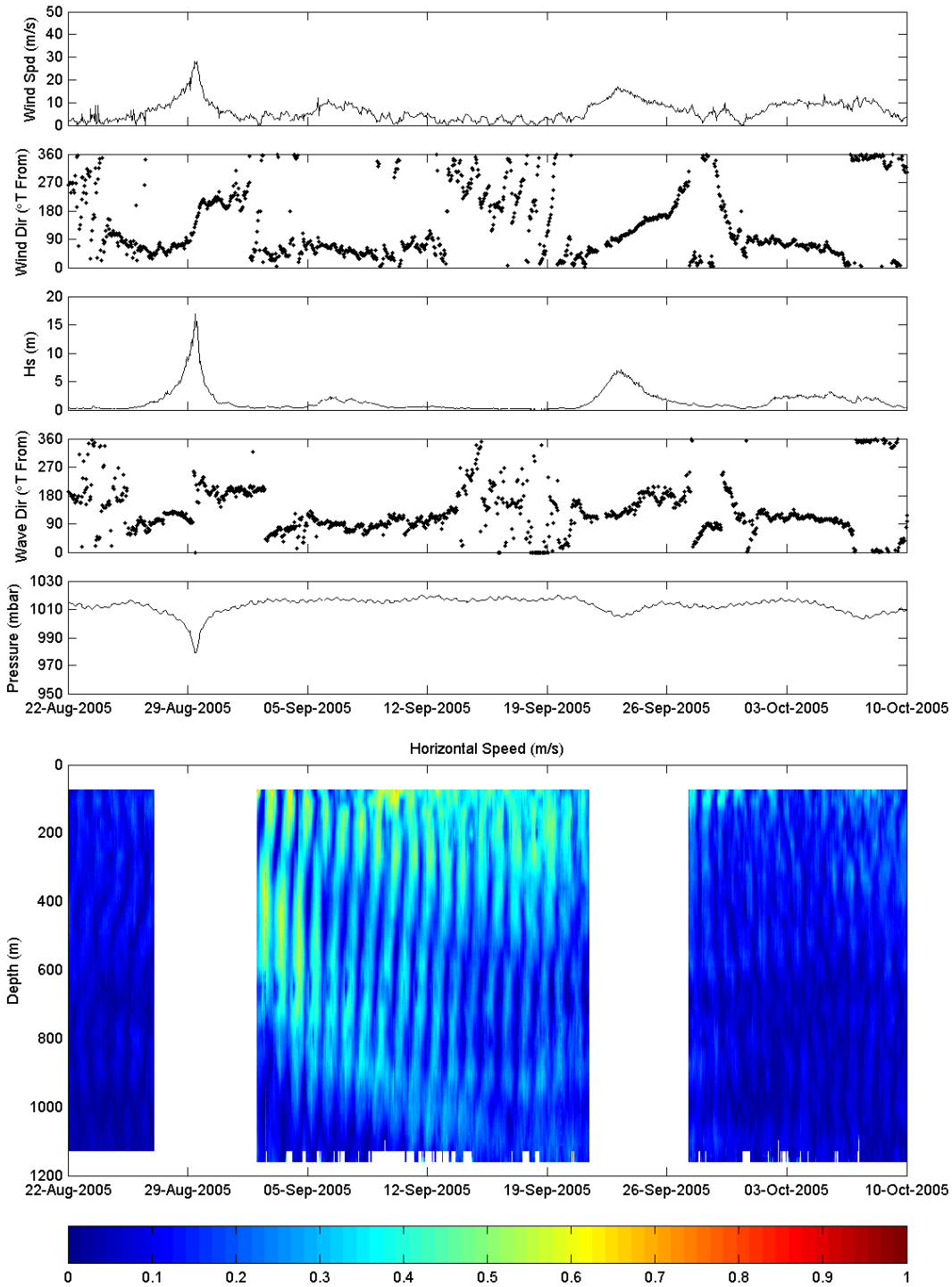

Figure 3-2: Hurricane Measurement at Buoy 42040 and NTL Station 42868 (28.164°N 88.484°W)

The circulation in the upper layer (surface to water depths of 800~1200 m) is dominated by Loop Current, LCE's and warm-core rings. Figure 3-3 shows the spatial frequency for the location of LCE centers. Eddies can affect a site for weeks to months per year.

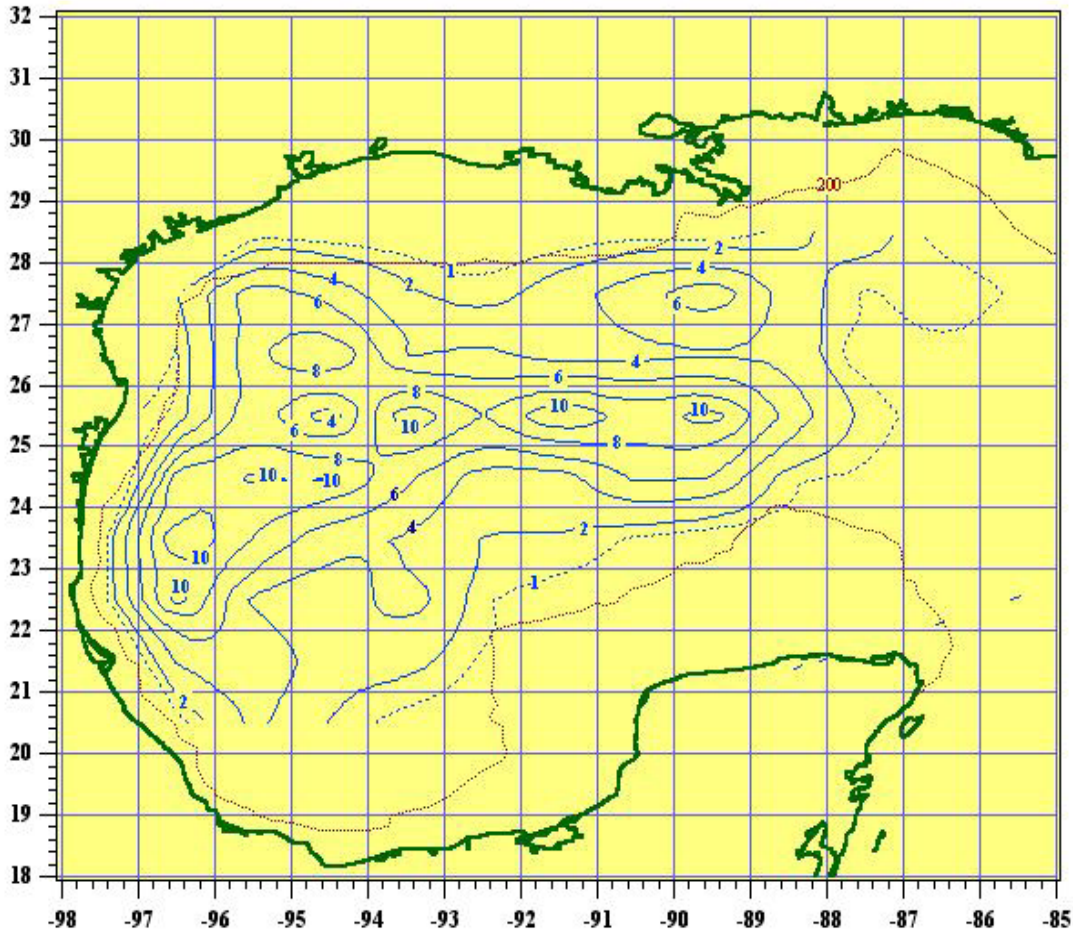

Figure 3-3: Spatial Frequency (%) for the Location of LCE centers using a 27-year (1977 – 2003) Database (From OCS Study MMS 2005-031)

The lower layer is dominated by deep eddies and Topographic Rossby Waves (TRWs). The deep eddies are generally vertically coherent in the lower layer, about 1,000 m above seabed, and effective in producing cross-isobath motions, hence possibly TRWs, with a tendency for bottom intensification. It is known that the relatively high lower-water-column current nearly depth independent and exist over the slope and rise in the northern GoM (the Desoto Canyon slope and the Sigsbee Escarpment).

Parasitic cyclones and jets can be generated when a warm eddy impinging upon a continental slope.

3.1.3 Current Kinetic Energy Distribution

The ocean current kinetic energy distribution was studied using high-resolution Princeton Regional Ocean Forecasting System (PROFS) model simulation. Figure 3-4 shows (um,vm) vectors superimposed on colour images of (KEm)1/2 at z = -250, -500, -800 and -1400 m. Thin black contours show 200 m, 2,000 m, 3,000 m and 3500 m isobaths.

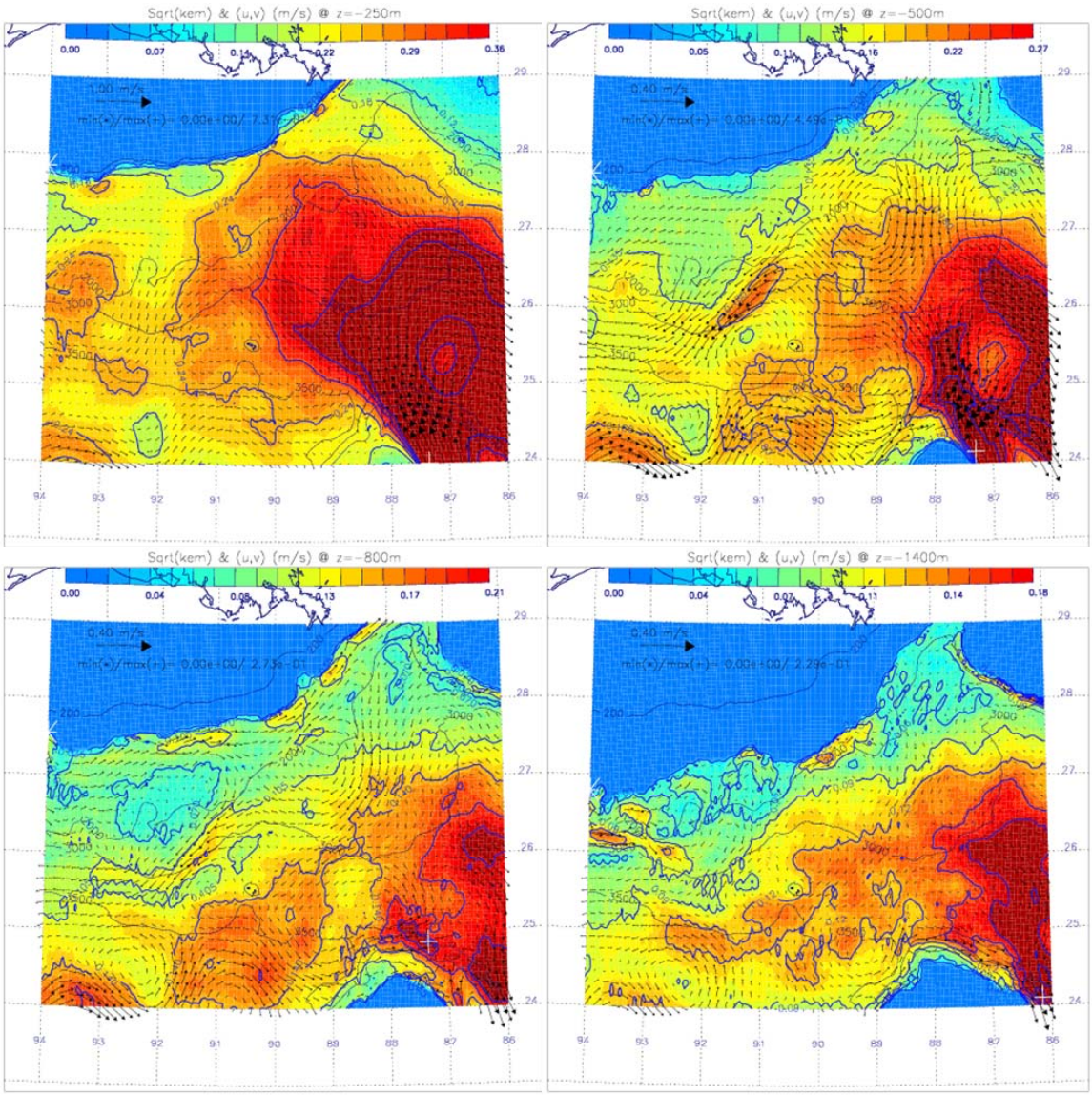

Figure 3-4: Mean Currents

At levels near the surface (e.g. z=-250 m in Figure 3-1), the mean currents (um,vm) are dominated by the Loop Current and remnants of eddies that were shed from the Loop and that propagate westward. The strong-current region extends north-westward from

the center of the Loop Current (near 86˚W- 24˚N) to south of the Mississippi Delta (near 90˚W- 28˚N), and also directly westward from the Loop. These surface features provide energy to the deeper layers of the Gulf, focusing in particular along isobaths and over the continental rise and slope of the northern Gulf as topographic Rossby waves. While examining the deeper current energy distributions provided in Figure 3-4, focus should be on stronger currents near localized topographic spots which we identified as "topocaustics" in Oey et al. (2009). Examples of these localized regions (zones) are listed in Table 3-1.

Table 3-1: Localized Regions (zones) of Strong Currents as Inferred from Figure 3-1

Name	Isobaths (m)	From Lon, Lat (˚W, ˚N)	To Lon, Lat (˚W, ˚N)	At z-level (m)
Lower Sigsbee	2,000~3,000	(92, 25.6)	(91.5, 26.5)	-500
SW DeSoto Canyon	1,000~3,000	(90, 27.6)	(88, 26)	All
Near-1,000 m	800~1,500	(92, 27.6)	(90.8, 27.7)	-800
		(90, 27.8)	(88, 29)	-800
Near-2,000 m	1,000~3,000	(94, 26.3)	(92, 25.8)	-1,400
	1,000~2,000	(90.5, 27.3)	(89, 27.6)	-1,400

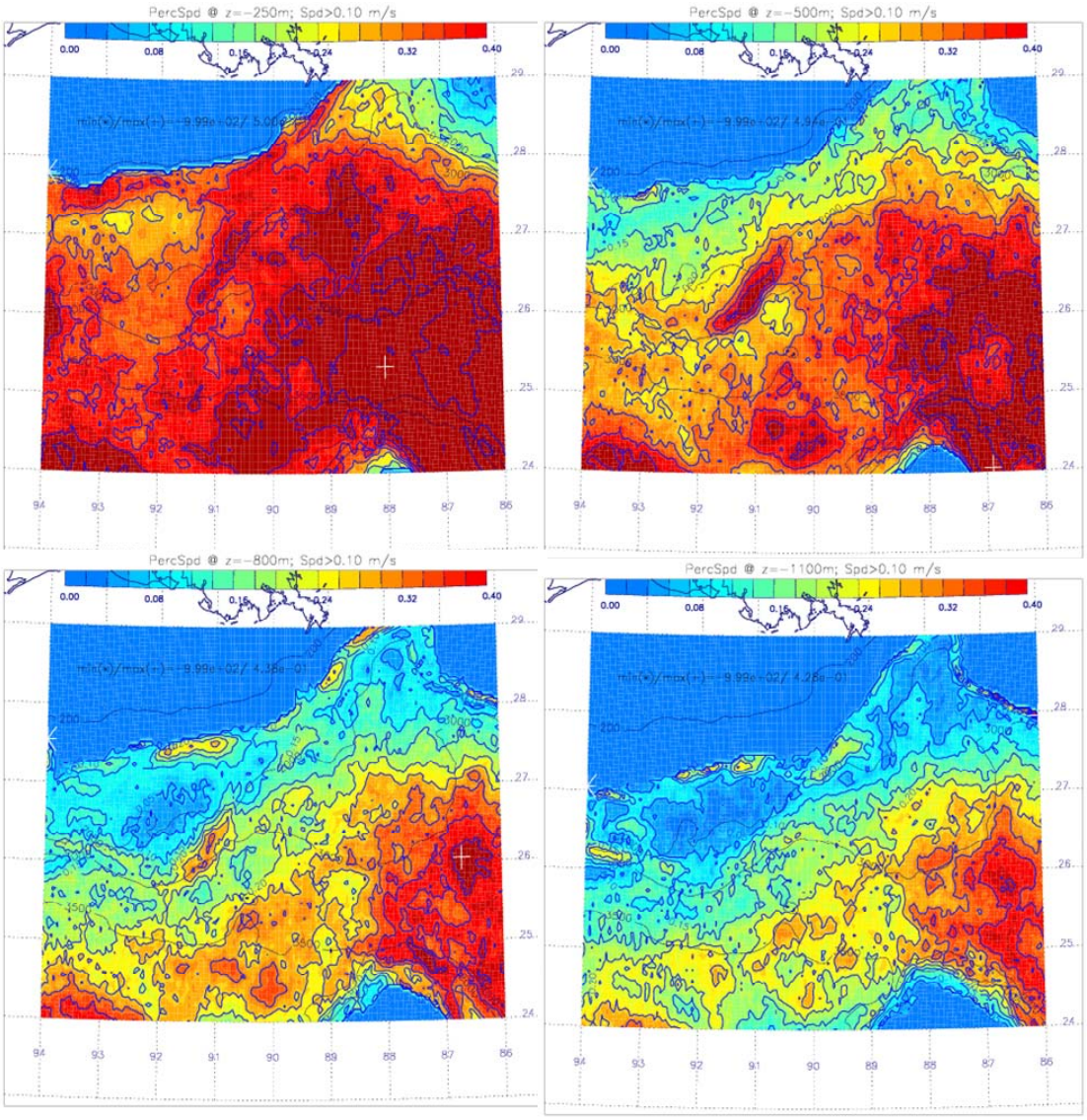

Figure 3-5: Color Maps and Contours of Frequency (x,speed) for speed=0.1 m/s

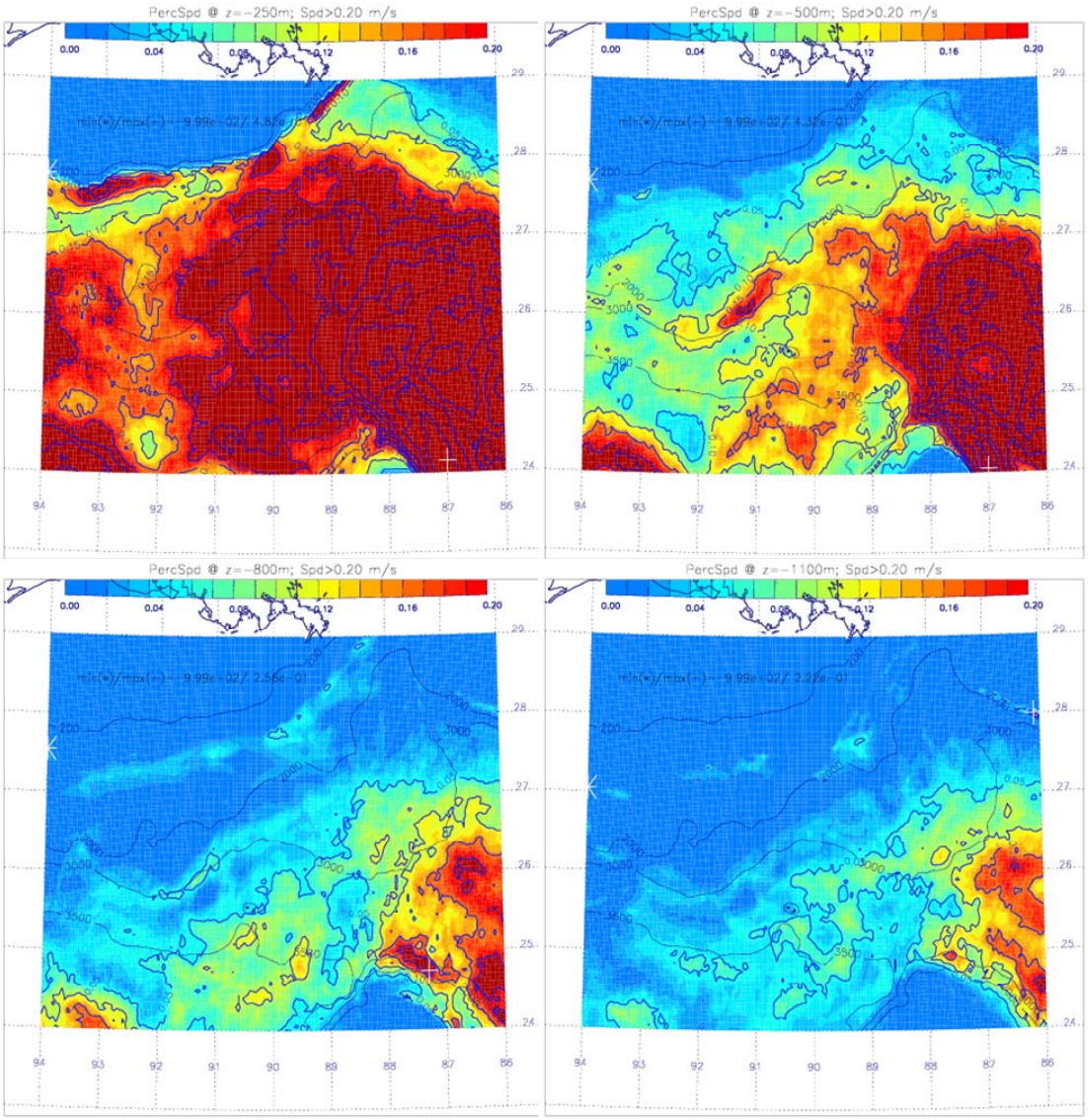

Figure 3-6: Color Maps and Contours of Frequency (x,speed) for speed=0.2 m/s

Figure 3-5 and Figure 3-6 show the frequency (Frq) of occurrences of the currents that are stronger than speed, for speed = 0.1 m/s (Figure 3-5) and 0.2 m/s (Figure 3-6) at z = -250, -500, -800 and -1100 m, respectively. In Figure 3-5, colour scale is from 0 to 0.4 (=40%) and contour (blue) interval is = 0.05 (=5%). However, in Figure 3-6 colour scale is from 0 to 0.2 (=20%) and contour (blue) interval is = 0.05 (=5%). Thin black contours show 200 m, 2,000 m, 3,000 m and 3,500 m isobaths. These confirm features listed in Table 1. For example, at the lower Sigsbee, Frq|0.1 is quite high, around 0.4 at z=-500 m, and 0.3 at z=-800 m (see Figure 3-5). Many of the features along the “Near-1,000 m”

also have relatively high Frq|0.1, and for speed=0.2 m/s (Figure 3-6), the values decrease to less than 0.05.

3.1.4 BOEMRE NTL ADCP and Mooring Current Data

In April 2005, BOEMRE (previously called the US Minerals Management Service (MMS)) issued a Notice to Lessees and Operators (NTL) regarding the reporting of ocean current data in the deep water of the GoM. An extensive body of NTL current data has since been collected by the offshore oil and gas industry and made available via the National Data Buoy Center (NDBC) web site.

Based on a comprehensive reanalysis and synthesis of existing data, a series of deepwater current studies were undertaken by BOEMRE. Notably are The Exploratory Study of Deepwater Currents in the GoM, the Survey of Deepwater Currents in the North-western GoM, the Survey of Deepwater Currents in the Eastern GoM, Dynamics of the Loop Current in U.S. Waters and other ongoing deepwater data collection.

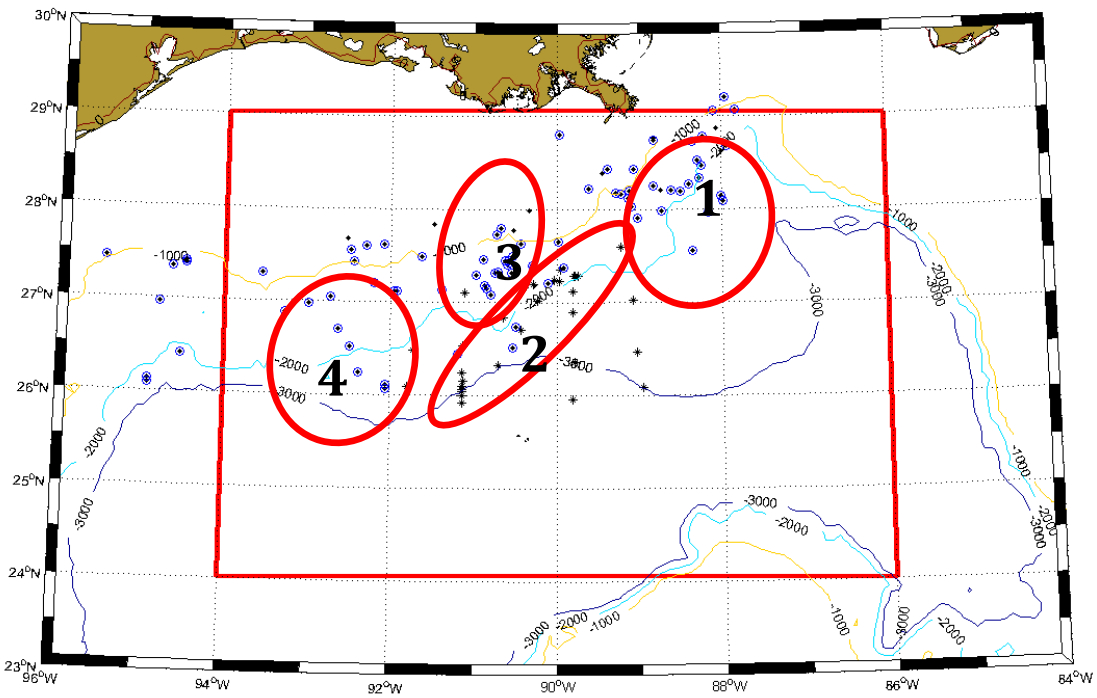

Figure 3-7: NTL ADCP Stations (circled dots) and Historical Current Mooring (+) Locations

Figure 3-7 shows the available NTL Acoustic Doppler Current Profiler (ADCP) and historical mooring data locations and also identifies the proposed representative zones

shown in previous figures. The red box is the zones in Figure 3-1, Figure 3-2 and Figure 3-3. The red ellipses are representative zones.

3.1.5 Zone Selection

The selection of representative study areas are based on current characteristics, ocean current kinetic energy distribution and observational data availability. The selected four zones are:

Zone 1 (DeSoto Canyon area)

This zone has the following characteristics:

- Very active lease area;
- The maximum northwestward Loop Current intrusion;
- Parasitic cyclones and jets can be generated when a warm eddy impinging upon continental slope;
- Two-layer jet with eastward flow at the surface and a return flow at depth;
- Deep penetrations and trapping of hurricane-induced inertial energy.

Zone 2 (base of the Sigsbee Escarpment area)

This zone has the following characteristics:

- New super-deep water oil & gas front (Petrobras' Cascade and Chinook, Chevron's Big Foot and Jack, BP's Atlantis and Shell's Stones etc.);
- TRW and bottom intensified current.

Zone 3

This zone has the following characteristics:

- Most active lease area;
- On the main path of LCE;
- Deep penetrations and trapping of hurricane-induced inertial energy.

Zone 4 (Keathley Canyon area)

This zone has the following characteristics:

- The new oil & gas front (BP's Kaskida, Anadarko's Lucius etc.);
- Local kinetic energy peak from 500 to 1,000 m;
- Possible TRW and bottom intensified current.

3.2 VIV ANALYSIS

3.2.1 General

In order to assess the significance of the current, VIV analysis had to be performed on the different riser configurations and TLP Tendon. This section provides details on the riser methodology that was adopted to perform the VIV analysis of different riser types using existing and new current data sets both for the long term and extreme current events.

3.2.2 Methodology

3.2.2.1 General

VIV fatigue analysis of the risers was performed using Shear7 V4.5 to confirm that the riser designs satisfied the VIV fatigue criterion.

VIV fatigue design was completed with both the existing and new current data sets for long term and extreme current events. For the SCRs, both in-plane and out-of-plane current directions to the risers were considered as part of the VIV design. But since all other riser types are axisymmetric, current in only one direction (in-plane or out-of-plane) needed to be considered.

The flowchart provided in Figure 3-8 shows the steps that were undertaken to perform VIV analysis on the different riser types.

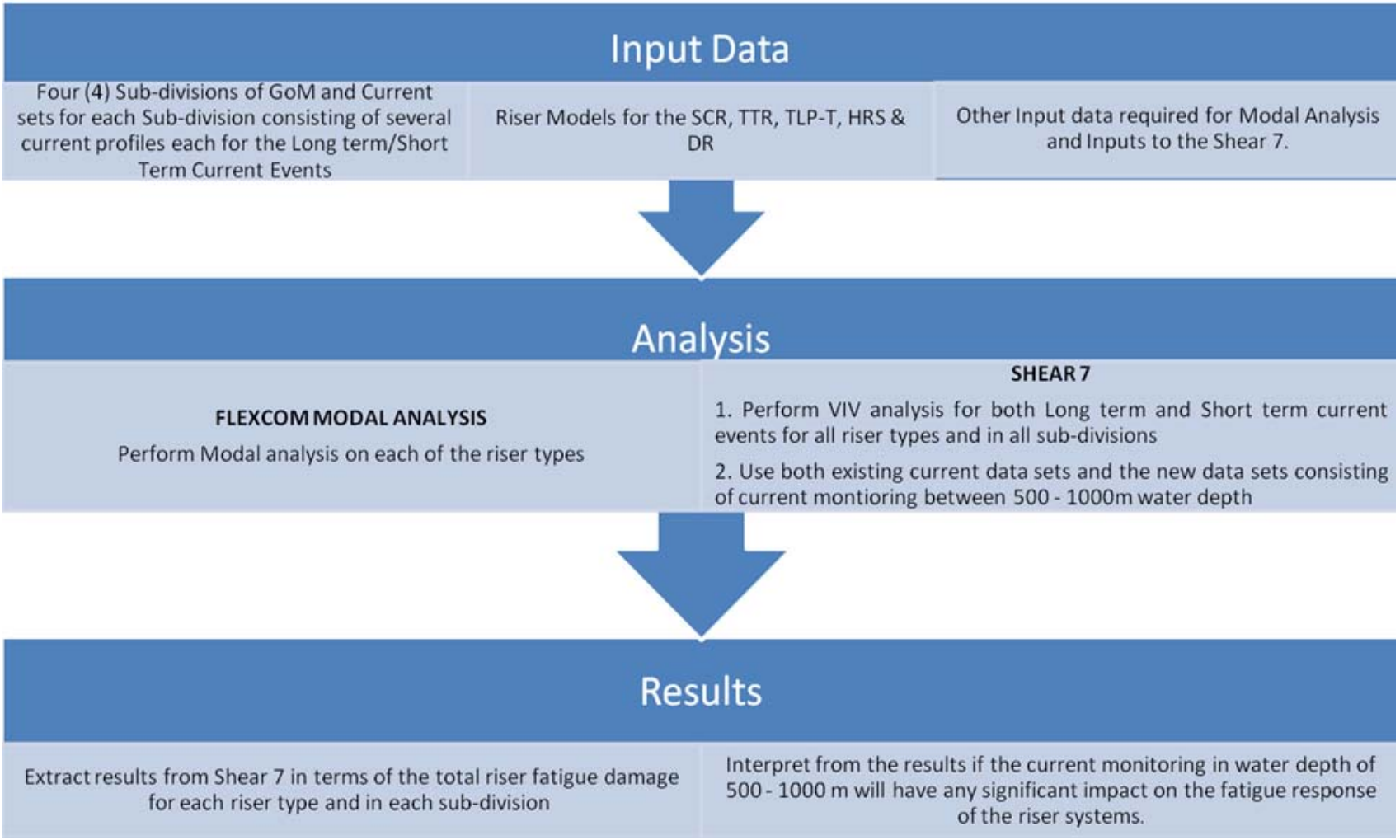

Figure 3-8: Flowchart of the VIV Analysis

3.2.3 Riser Model Selection

3.2.3.1 General

In this study, the GoM was divided into 4 separate zones, based on the current characteristics. The ranges of water depth (minimum and maximum water depth) for each zone are summarized in Table 3-2.

Table 3-2: Ranges of Water Depth of Different Zones of the GoM

Zones	Minimum Water Depth (m)	Maximum Water Depth (m)	Mean Depth (m)
1	980	2,438	1,871
2	1,286	2,956	2,045
3	805	2,417	1,369
4	1,610	2,249	1,992

The following methodology was adopted to select the current profiles and specific riser models for each type (Drilling, SCR, TTR, Hybrid Risers, and TLP Tendons), in order to populate a matrix of analysis cases that were the basis for the study conclusions.

The main aim of the study is to compare the VIV damage caused due to the existing and the new current profiles, and thus to conclude if there is a need for current monitoring between 500 m-1,000 m water depth in GoM.

The conclusions of the study were based on the comparison analysis; so, as long as the riser design was kept similar for both new (proposed) and existing (base) current conditions, the conclusions would be valid for all zones and types of developments.

3.2.3.2 Current Selection

In order to perform the comparison, two current profiles are required.

Existing Current Profiles. These are existing current profiles that are normally used in VIV analysis and mostly do not include current magnitude in the water depth range of 500 m-1,000 m, or they have very limited amount of data which represent the significant events in 500 m-1,000 m water depth.

New Current Profiles. These include current information within the water depth ranges of 500 m-1,000 m. An example of the new/updated current profiles is presented in Figure 3-9.

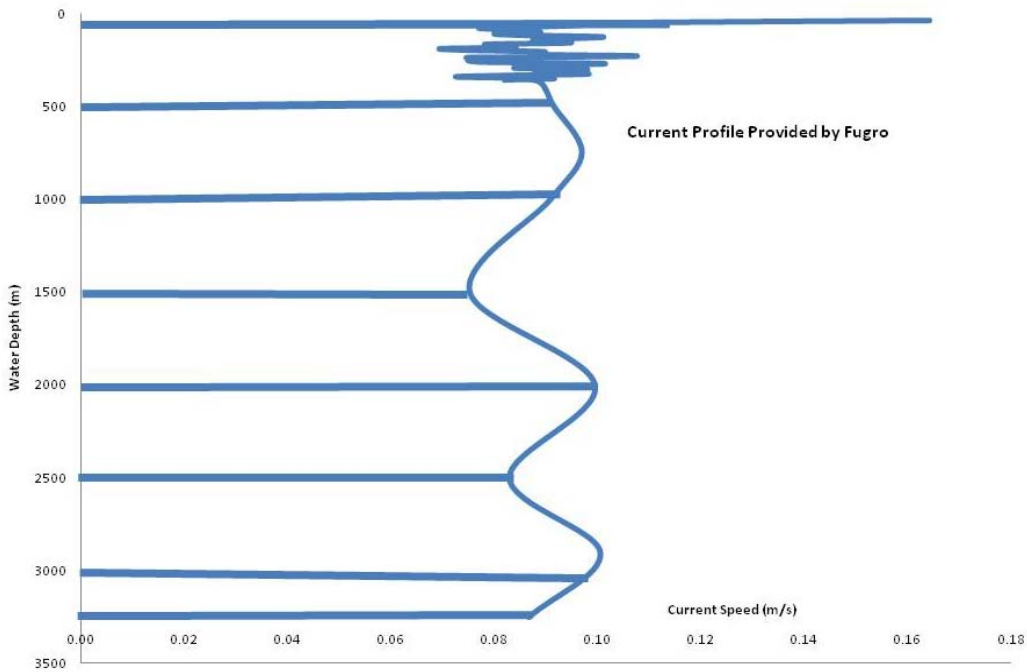

Figure 3-9: Example of New Current Profile

Due to lack of information on existing current profile, the "existing" current data is created utilizing the "new" current data by eliminating the current magnitude between 500 m-1,000 m water depth, as shown in Figure 3-10. The eliminated current data is then substituted with a linear profile between the water depths of 500 m and 1,000 m, as shown in the same figure. "Existing" profiles thus generated are quite similar to those currently used to perform the VIV analysis. VIV results based on the "existing" profiles (with 1-2 data points between 500 m-1,000 m water depth range) can then be compared with those based on the new profiles (with sufficient details of the current between 500 m-1,000 m water depth).

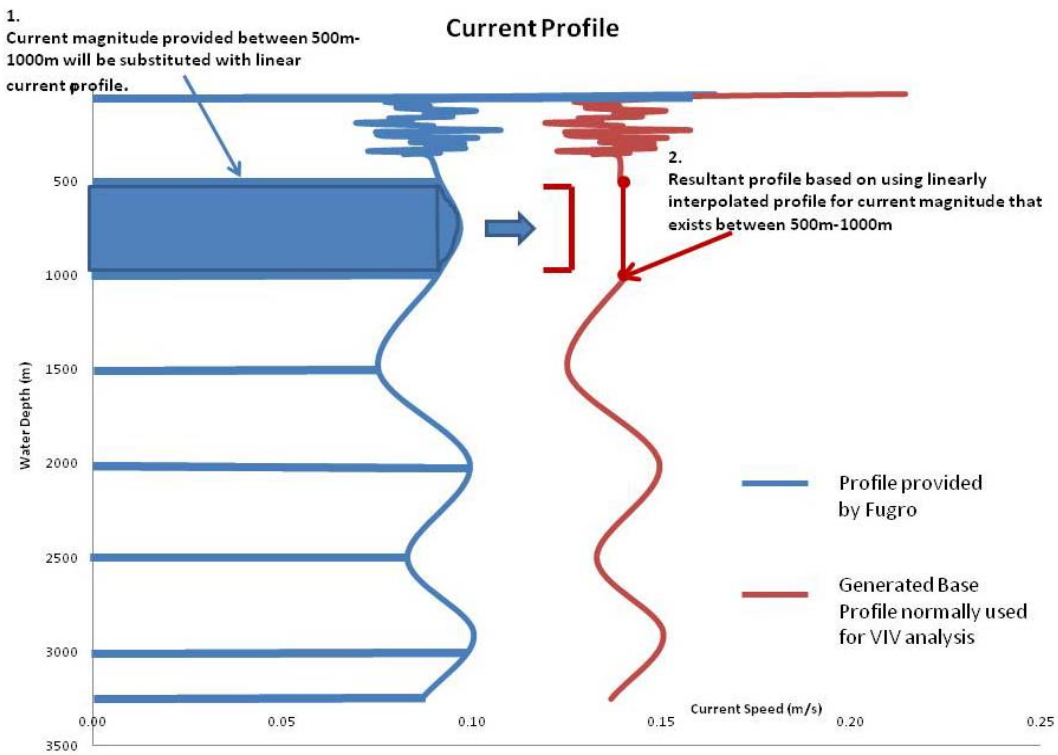

Figure 3-10: Existing Current Profile Created from the New Current Profile

3.2.3.3 Load Case Matrix

It was identified that there are a number of variables that may have an effect on the VIV response of riser systems. These parameters include:

- Water Depth;
- Riser Types;
- Current Profiles;
- Zones (Location).

To cover possible scenarios, the following water depths were considered for all zones:

- Shallower Water Depth (4,000 ft);
- Deep Water Depth (7,000 ft).

Based on the above discussion, a load case matrix was compiled and summarized in Table 3-3.

Table 3-3: Load Case Matrix

Parameter	Value	Description
Riser Type	5	Steel Catenary Riser (SCR,) Top Tension Riser (TTR), Tension Leg Platform - Tendon (TLP-T), Drilling Riser (DR), Hybrid Riser System (HRS)
Zones	3	Zone 1 (DeSoto Canyon area) Zone 2 (base of the Sigsbee Escarpment area) Zone 3 (Most Active, Penetration and trapping of hurricane-induced inertial energy)
Current Sets	2	Long term Current Extreme Current
Current Scenario	2	Existing current data (consisting of current distribution up to 500 m and then a linear profile between the water depths of 500 m and 1,000 m) New current data (consisting of current distribution up to 1,000 m)
Water Depth	2	Shallower water depth (~4,000 ft), and Deep Water Depth (7,000 ft)
Total VIV Cases	120	

This is an exhaustive load case matrix, and it is quite cost prohibitive to analyze all these cases. MCSK recommended a strategy to make use of select load cases for the study yet still provide comprehensive conclusions. Details of the strategy/methodology are explained below and in Figure 3-11. All the analyses identified in Steps 1, 2 and 3 were performed for the same current sets and scenarios listed in Table 3-3.

Step 1:

In **Step 1**, the water depth effect on a single riser system at the most onerous zone was studied. SCR was selected for this analysis, because SCR can be used in varied water depth ranges and also there has been more interest in SCRs in the GoM in recent years. Drilling Risers could also be studied; however, the VIV effect on the drilling riser is a shorter term effect, and the effects might not be fully captured. SCR was modeled and studied for the different water depths (shallow, mid- and deep-water).

After identifying which water depth had an effect on VIV between the water depth ranges of 500 m to 1,000 m, the effect of riser type was studied for that water depth, as detailed in **Step 2**.

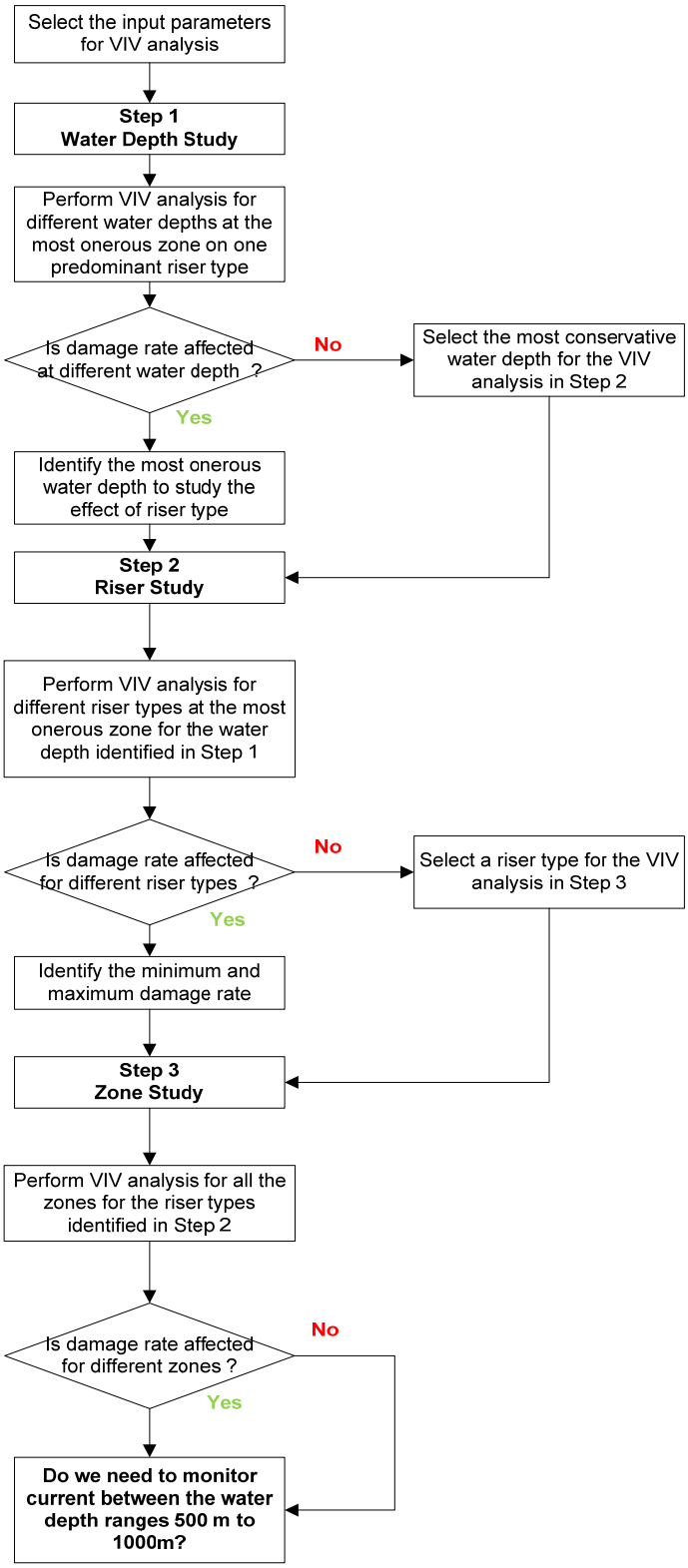

Figure 3-11: Riser Analysis Methodology

Step 2:

In **Step 2**, riser type effect for the water depth identified in **Step 1** was considered at the most onerous zone. The most onerous zone was selected with the help of Fugro and Princeton, and all riser types were analyzed. The riser types experiencing the least and worst damage rate were identified, and the best and worst case were analyzed at different zones. This was done to help identify if the other zones might have an effect on the damage rate for the least affected riser type. The details are explained in **Step 3**.

Step 3:

In **Step 3**, the zone effect on the riser types which have a maximum and minimum damage rate, identified in **Step 2**, were studied. Namely, VIV analysis was performed on the riser systems identified in **Step 2**, for all 4 zones.

Based on the above methodology, the modified load case matrix was compiled and summarized below in Table 3-4.

Table 3-4: Modified Load Case Matrix

Analysis	Parameter	Value	Description
Step 1 - Water Depth Study	Riser Type	1	SCR
	Zones	1	Most Onerous Zone
	Current Sets	2	Long term Current
			Extreme Current
	Current Scenario	2	Existing current data (consisting of current distribution up to 500 m and then a linear profile between the water depths of 500 m and 1,000 m)
			New current data (consisting of current distribution up to 1,000 m)
	Water Depth	2	Shallower water depth (~4,000 ft), and Deep Water Depth (7,000)
	Total VIV Cases in Step 1	**8**	
Step 2 - Riser Type Study	Riser Type	5	SCR, TTR, TLP-T, DR, HRS
	Zones	1	Most Onerous Zone
	Current Sets	2	Long term Current
			Extreme Current
	Current Scenario	2	Existing current data (consisting of current distribution up to 500 m and then a linear profile between the water depths of 500 m and 1,000 m)
			New current data (consisting of current distribution up to 1,000 m)
	Water Depth	1	Most Conservative Water Depth
	Total VIV Cases in Step 2	**20**	
Step 3 - Zone Study	Riser Type	2	2 Riser Types selected from Step 2
	Zones	3	Zone 1 (DeSoto Canyon area)
			Zone 2 (base of the Sigsbee Escarpment area)
			Zone 3 (Most Active, Penetration and trapping of hurricane-induced inertial energy)
	Current Sets	2	Long term Current
			Extreme Current
	Current Scenario	2	Existing current data (consisting of current distribution up to 500 m and then a linear profile between the water depths of 500 m and 1,000 m)
			New current data (consisting of current distribution up to 1,000 m)
	Water Depth	1	Most Conservative Water Depth
	Total VIV Cases in Step 3	**24**	
	Total VIV Cases	**52**	

3.2.4 Riser Analysis Technique

Riser analysis steps are summarized below:

3.2.4.1 Preparation of Model Input

Riser models were created for each riser type extending from the touchdown point to the riser-vessel hang-off location. Modal analysis was performed for each of the riser systems to obtain different modal shapes etc.

The data obtained from the modal analysis was further utilized as an input for the Shear 7 analysis. Shear 7 is the commercially available software which is widely used in the industry to perform the VIV analysis and calculate the damage in the riser systems.

3.2.4.2 Preparation of Shear7 Input

Shear7 models all risers as if they were top-tensioned and vertical. Therefore, in order to model a riser, it was necessary to model the riser as an equivalent vertical pipe. This was achieved by modifying the current profiles and applying them at the appropriate location along the riser.

Current profiles were assumed to act normal to the longitudinal axis of the riser. This assumption is correct for out-of-plane currents (currents normal to the plane of the riser). For in-plane currents where the angle of the current relative to the riser is other than 90° to the riser plane, the current was normalized based on the cosine of the angle where the angle used was the angle between the current (horizontal) and the riser vector at each elevation for which the current was defined.

3.2.4.3 User-Defined Parameters for VIV Analysis

Parameters that remained constant and were user defined are given in Table 3-5. These parameters are subject to change depending on the specific riser system.

Table 3-5: Parameters for VIV Analysis

Parameter	Value (Bare Riser)	Straked Riser
Strouhal Number	0.18	
Reduced Velocity Bandwidth	0.7-1.0	
Power Ratio Cut-off	0.05	
Primary Zone Amplitude Limit	1.0	
Structural Damping Coefficient	0.003	
Lift Coefficients Reduction Factor	1.0	
Lift Coefficient Table	1	3
Power Ratio Exponent	1.0	
Added Mass Coefficient	1.0	2.0

3.2.4.4 Estimate of Fatigue Damage and S-N Curves

Fatigue damage is expected to occur under the cyclic loading of VIV. Generally, fatigue damage is estimated using either of two approaches; namely the S-N and Fracture-Mechanics approaches. The former is more commonly used by the industry, as it is simpler and requires less parameters, while the latter is typically used in the more critical situations and locations. The S-N approach utilizes empirical relations (curves) that estimate the number of load cycles to failure (N) under the effect of cycling a specific stress range (S). The S-N relations (curve) are usually of the form

$$N = C_2 / S^m$$

Where,

N = Number of cycles to failure under constant stress range, S;

S = Constant stress range;

m = Inverse slope of the S-N curve

The S-N curve adopted in this study is the B curve from DNV RP C203, which is commonly used for bare riser material and presented in Table 3-6. A stress concentration factor (SCF) of 1.0 was assumed for the entire length of the riser. However, the final conclusion of the study is not expected to be particularly sensitive to the specific curve or SCF used, as the study concerns comparisons between cases that use the same S-N curves and SCF's.

Table 3-6: S-N Curve Used in the Study

Material	S-N curve	m	S	Application
Base Metal	DNV-B	4.0	4.47E+11	Base metal

3.2.5 Damage Calculation

Based on the riser analysis, damage was calculated for each current bin and for each current profile. The cumulative damage from all the bins for all the current profiles in one set (long term or extreme) provides the damage to the riser due to that set.

Similar, analysis was performed for different riser types and for different zones.

3.3 Description of Riser Systems

Following is the set of riser types that were addressed in the VIV analysis:

- Steel Catenary Riser (SCR)
- Top Tensioned Riser (TTR)
- Hybrid Riser System (HRS)
- Drilling Riser (DR)
- TLP Tendon (TLP-T)

These riser systems represent the entire range of riser systems that are currently used in the GoM. Generally, each of these riser systems may consist of Semi, TLP, SPAR or a FPSO as their topside facilities. Since during the VIV analysis, the damage is assessed due to the current along the riser depth and it does not involve any contribution form the topside vessel, the selection of topside facility is immaterial to the study.

3.4 General

This section provides the input data required to perform analysis for all the different types of riser systems forms the basis of design the riser/ mooring systems. This includes, but not limited to, the following:

- Relevant information regarding the riser systems;
- Critical design parameters that form the basis of design for this study;
- Relevant information regarding the current profiles.

Under operating conditions draft of 100 ft is assumed for all the riser systems.

3.5 Environmental data

Current profiles provided by Fugro and Princeton are attached to this report as MS Excel spreadsheets.

4.0 RESULTS

This study was performed to assess the significance or effect of the current data existing between 500 m-1,000 m water depth range on the VIV performance of different riser configurations and TLP tendons.

The comparison of the VIV fatigue damage was performed for long term and extrene events for the various water depths, different riser systems and for different zones of the GoM.

The results from the study are presented as a comparison of fatigue life for the considered riser systems and tendons using the existing and the new current profiles.

The existing current profile is generated from the new profile by eliminating the current data points in the range of 500 m-1,000 m water depth and replacing it with the linear current profile as shown in Figure 3-10.

For the Steel Catenary Risers (SCR), both in-plane and out-of-plane current directions are considered as part of the VIV design and hence the results are presented separately. All other riser types are axisymmetric, and hence current in only one direction captures the maximum resultant fatigue damage through the structure.

4.1 STEP 1: Water Depth Study

The study was performed to assess the impact of water depth on the VIV damage for both long term and extreme events while keeping all other parameters constant. The study was performed using a Steel Catenary Riser (SCR).

In step 1, SCR configuration was modeled in 4,000 ft and 7,000 ft of water depth. VIV fatigue damage/life for a Steel Catenary Riser (SCR) was then calculated based on the new and the existing current profile. The in-plane fatigue life and the out-of-plane fatigue life were calculated for each current profile and for both the water depths.

4.1.1 Long Term Event

Figure 4-1shows the in-plane fatigue damage comparison of a SCR between the Existing and New current prolife along the length of the structure from the hang-off point to the touch down point at a water depth of 4,000 ft (all graphs show measurements from the hang-off to the touch down point).

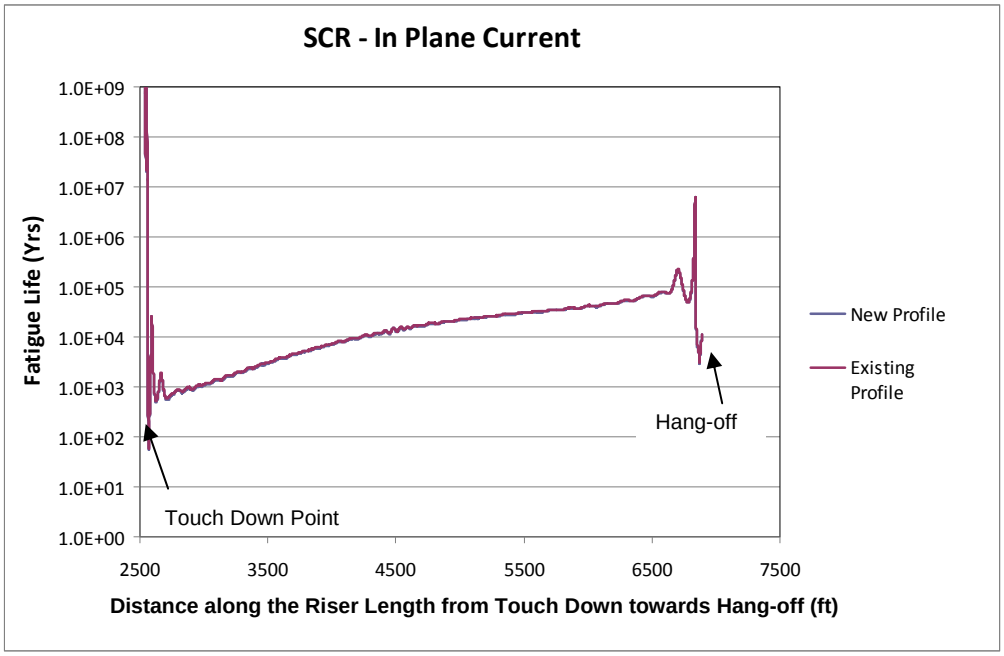

Figure 4-1: Comparison between VIV fatigue damages caused by existing and new profiles (Zone = 2, Water Depth=4,000ft, Event = Long-term, VIV type = In-plane, Riser Type = SCR)

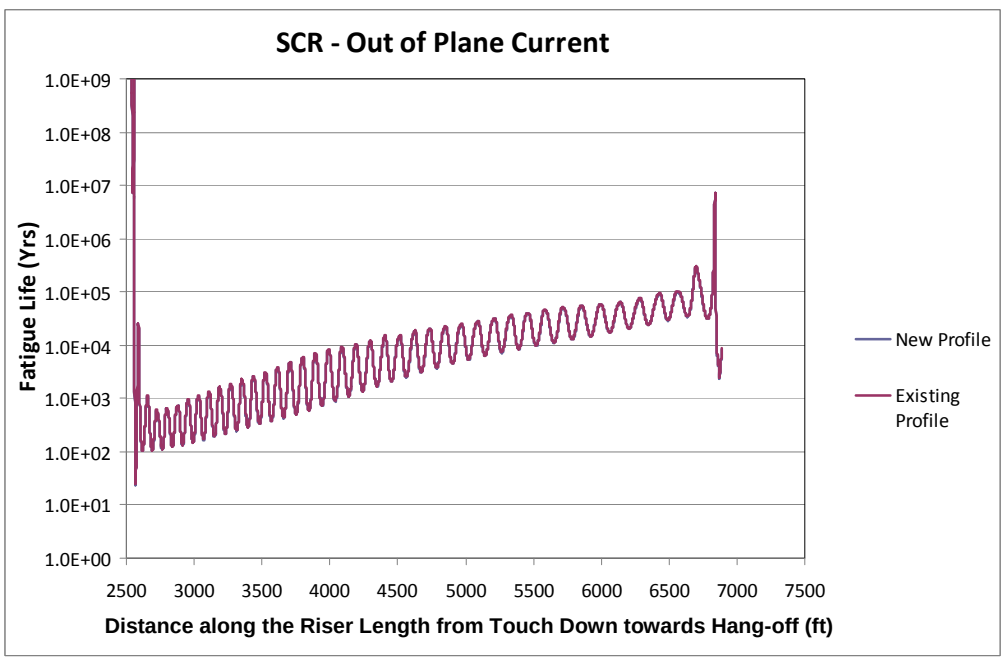

Figure 4-2: Comparison between VIV fatigue damages caused by existing and new profiles (Zone = 2, Water Depth=4,000ft, Event = Long-term, VIV type = Out-of-plane, Riser Type = SCR)

Figure 4-2 shows the out-of-plane fatigue damage comparison between the Existing and the New current profile of a SCR at a water depth of 4,000 ft. Similarly, Figure 4-3 shows the in-plane fatigue damage comparison of a SCR between the Exiting and New current profile at a water depth of 7,000 ft which was done just for completeness.

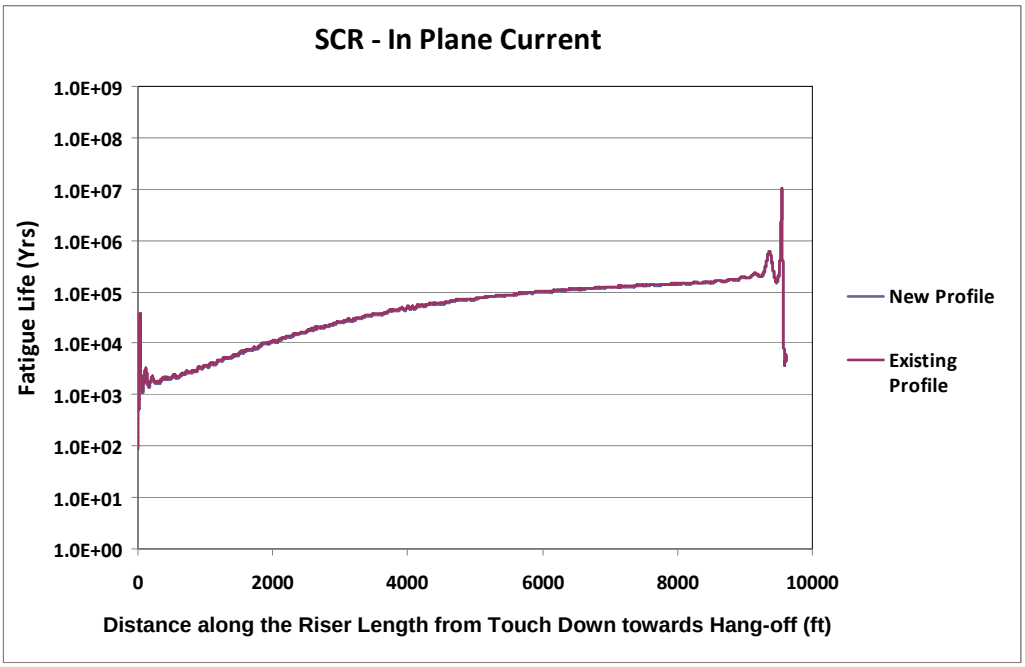

Figure 4-3: Comparison between VIV fatigue damages caused by existing and new profiles (Zone = 2, Water Depth=7,000ft, Event = Long-term, VIV type = In-plane, Riser Type = SCR)

Table 4-1: Long-term Fatigue Damage Calculation for SCR

	Water Depth (ft)	Fatigue Life (yrs)		Damage Rate		% Different in Damage between Existing and New Current Profile
		Existing	New	Existing	New	
In-Plane	4,000 ft	59	56	0.012/yr	0.018/yr	-2.7%
	7,000 ft	87	85	0.011/yr	0.012/yr	-1.8%
Out-of-Plane	4,000 ft	24	23	0.041/yr	0.042/yr	-5.7%

Based on the outcome of the study performed for Step 1 on fatigue damage comparison of a steel catenary riser between the Existing and New current profile, it was concluded that there is no significant difference between the current profiles at water depths of 4,000 ft and 7,000 ft.

4.1.2 Extreme Event VIV Fatigue Analysis

Figure 4-4 shows the in-plane extreme event fatigue damage comparison of a SCR between the Existing and New current prolife along the length of the structure from the hang-off point to the touch down point at a water depth of 4,000 ft (all graphs show measurements from the hang-off to the touch down point).

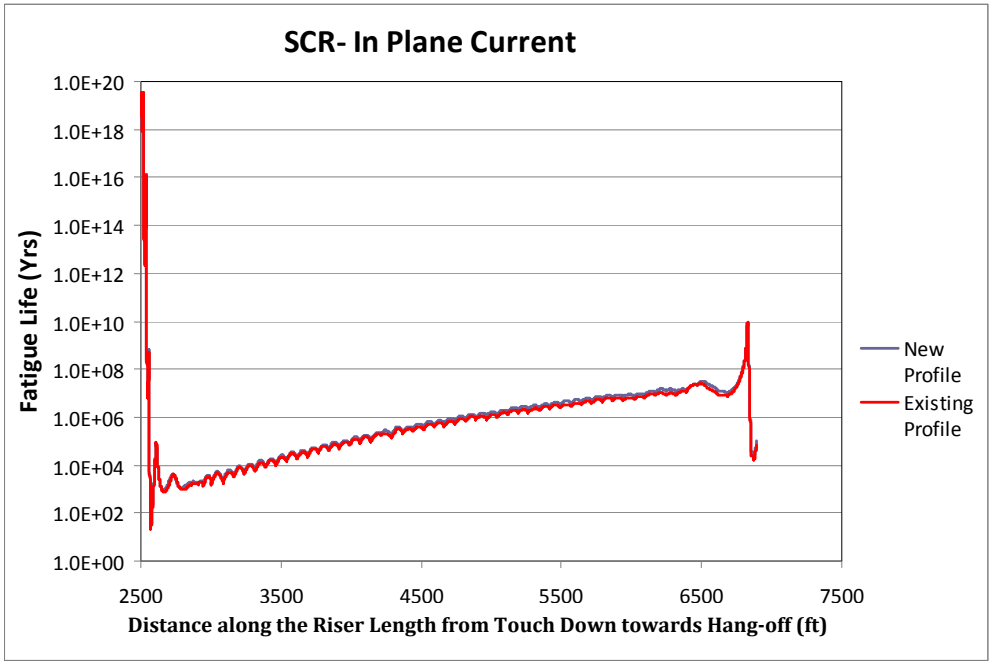

Figure 4-4: Comparison between VIV fatigue damages caused by existing and new profiles (Zone = 2, Water Depth=4,000ft, Event = Extreme, VIV type = In-plane, Riser Type = SCR)

Table 4-1 presents the extreme event damage calculations for the SCR at water dept of 4,000 ft for Zone 2.

Table 4-2: Extreme Event Fatigue Damage Calculation for SCR

	Water Depth (ft)	Fatigue Life (yrs)		Damage Rate		% Different in Damage between Existing and New Current Profile
		Existing	New	Existing	New	
In-Plane	4,000 ft	22.4	27.6	0.044518/yr	0.036178/yr	+23.05%

Based on the outcome of the study performed for Step 1 on fatigue damage comparison of a steel catenary riser between the Existing and New current profile, it was concluded

that there is no significant difference between the current profiles at water depths of 4,000 ft for extreme event VIV fatigue damage calculation.

4.2 STEP 2: Riser Type Study

Step 2 attempted to assess the difference between the VIV fatigue life from New and Existing current profile for different riser types. The outcome of the study was expected to provide guidance on the most critical riser types in terms of variation in the VIV fatigue damage while using existing and the new current profiles.

For this study all other parameters were kept constant. The water depth was kept constant at 4,000 ft.

4.1.3 Long Term Event

As previously stated (Figure 3-7), the GoM was divided into zones. For this study, the ideal zone to choose would have been the zone that would give the maximum difference between the New and Existing current profiles.

Zone 2 was selected since this has the maximum kinetic energy which could create a large amount of disturbance leading to a greater difference between the two current profiles.

A water depth of 4,000 ft was selected because in step 1, it showed a higher percent difference in damage between the Existing and New current profile.

Figure 1-1 shows the in-plane fatigue damage for an SCR at 4,000 ft.

Figure 4-5 shows fatigue life a TLP-tendon at 4,000 ft; Figure 4-6 shows the fatigue damage for the drilling riser at 4,000 ft; Figure 4-7 shows the comparison of fatigue damage for a TTR-composite riser; and Figure 4-8 shows fatigue damage for a Hybrid Riser at 4,000 ft.

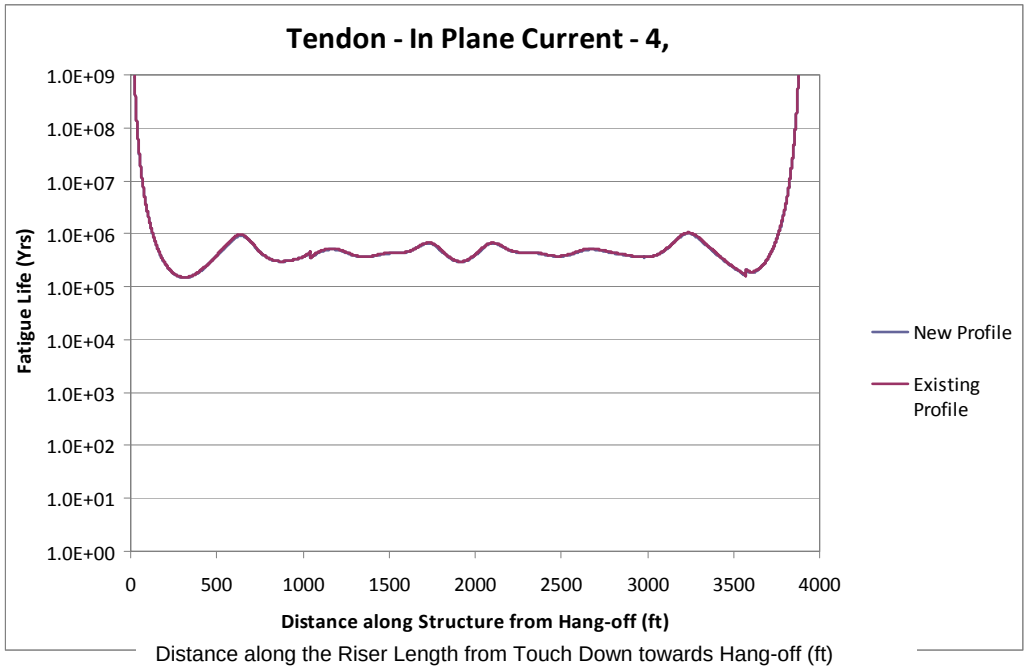

Figure 4-5: Comparison between VIV fatigue damages caused by existing and new profiles (Zone = 2, Water Depth=4,000ft, Event = Long-term, VIV type = In-plane, Type = Tendon)

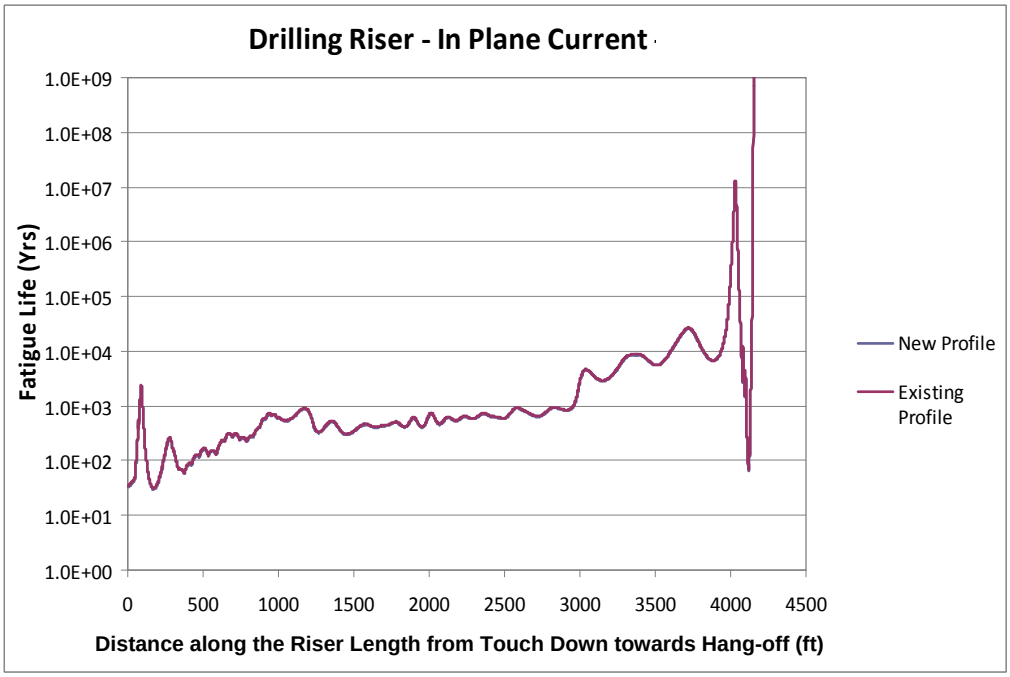

Figure 4-6: Comparison between VIV fatigue damages caused by existing and new profiles (Zone = 2, Water Depth=4,000ft, Event = Long-term, VIV type = In-plane, Riser Type = Drilling Riser)

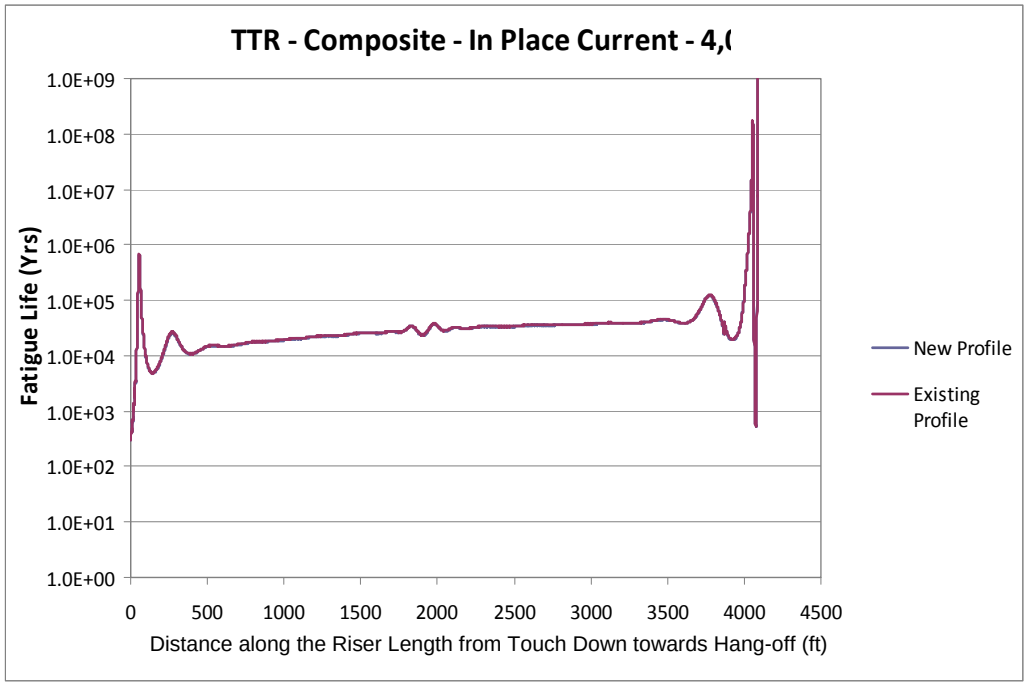

Figure 4-7: Comparison between VIV fatigue damages caused by existing and new profiles (Zone = 2, Water Depth=4,000ft, Event = Long-term, VIV type = In-plane, Riser Type = TTR)

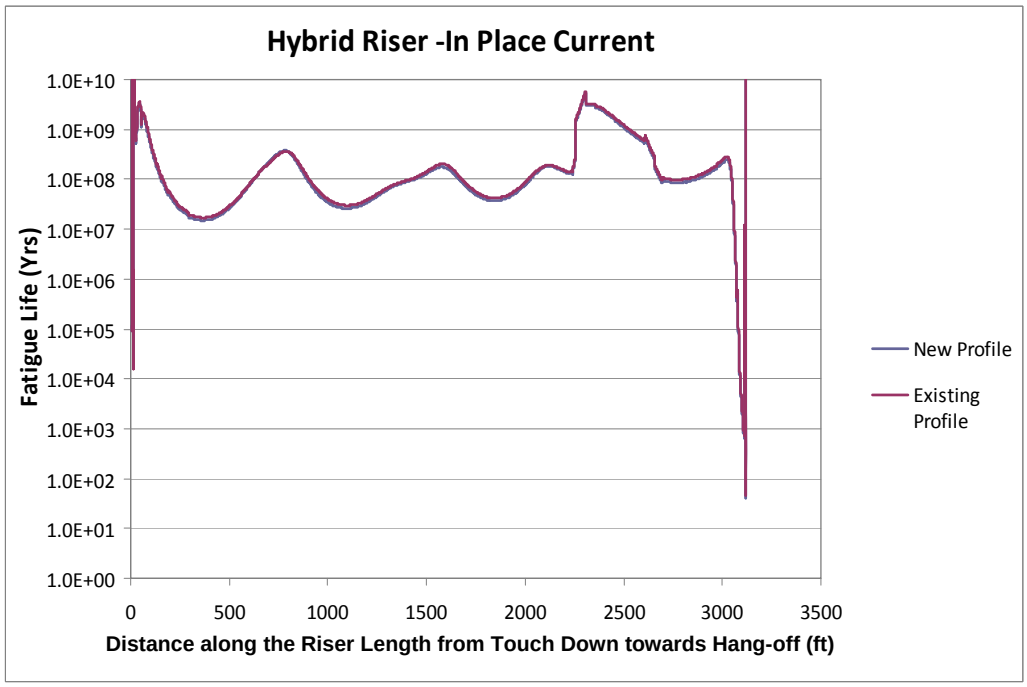

Figure 4-8: Comparison between VIV fatigue damages caused by existing and new profiles (Zone = 2, Water Depth=4,000ft, Event = Long-term, VIV type = In-plane, Riser Type = Hybrid Riser)

Based on the results obtained from Step 2, fatigue life in terms of years, damage rate per year and percent different in damage between the Existing and New current profiles for each riser type is provided in Table 4-3.

Table 4-3: Long-term In-Place Damage Assessment Calculation for all Riser Types for Zone 2

Water Depth (ft)	Riser Type	Fatigue Life (yrs)		Damage Rate		% Difference in Damage between Existing and New Current Profiles
		Existing	New	Existing	New	
4,000 ft	SCR	59	56	0.012/yr	0.018/yr	-2.7%
	Tendon	1.51E05	1.48E05	6.64E-06/yr	6.76E-06/yr	-1.8%
	Drilling Riser	30	29	0.032/yr	0.033/yr	-3.5%
	TTR	308	297	0.003/yr	0.003/yr	-3.4%
	Hybrid	45.5	39.5	0.022/yr	0.025/yr	-13.0%

According to the results obtained from step 2, it appears that the hybrid riser has the highest percent difference of damage between the Existing and New current profiles.

4.1.4 Extreme Event VIV Fatigue Analysis

Figure 4-9 shows extreme event fatigue life of a TLP-tendon at 4,000 ft; Figure 4-10 shows the extreme event fatigue damage for the drilling riser at 4,000 ft; Figure 4-11 shows the comparison of extreme event fatigue damage for a TTR-composite riser; and Figure 4-12 shows extreme event fatigue damage for a Hybrid Riser at 4,000 ft.

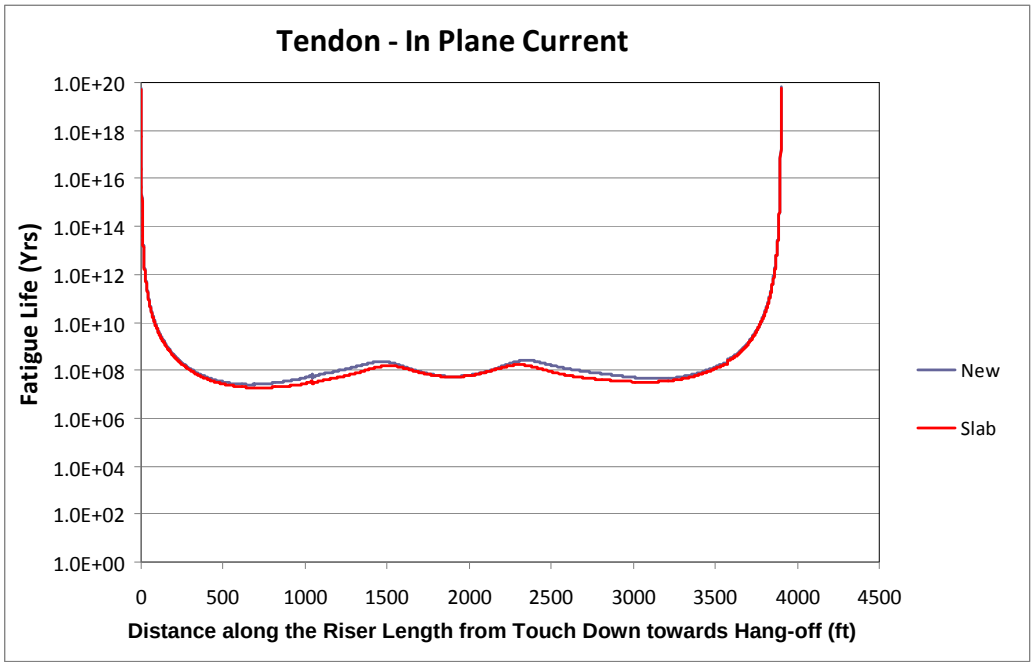

Figure 4-9: Comparison between VIV fatigue damages caused by existing and new profiles (Zone = 2, Water Depth=4,000ft, Event = Extreme, VIV type = In-plane, Type = Tendon)

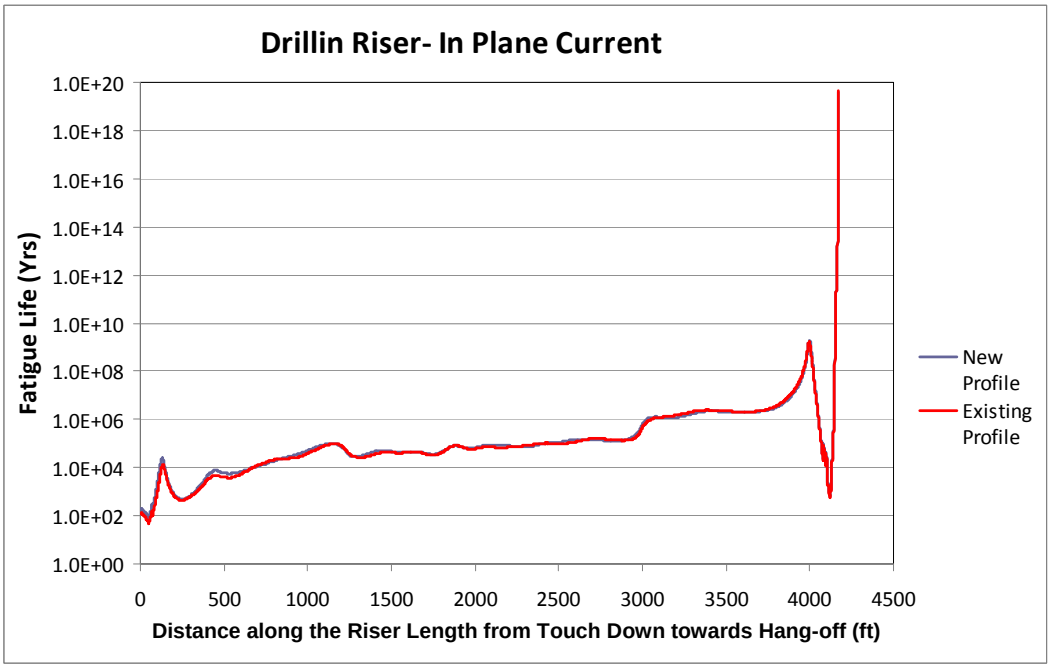

Figure 4-10: Comparison between VIV fatigue damages caused by existing and new profiles (Zone = 2, Water Depth=4,000ft, Event = Extreme, VIV type = In-plane, Riser Type = Drilling Riser)

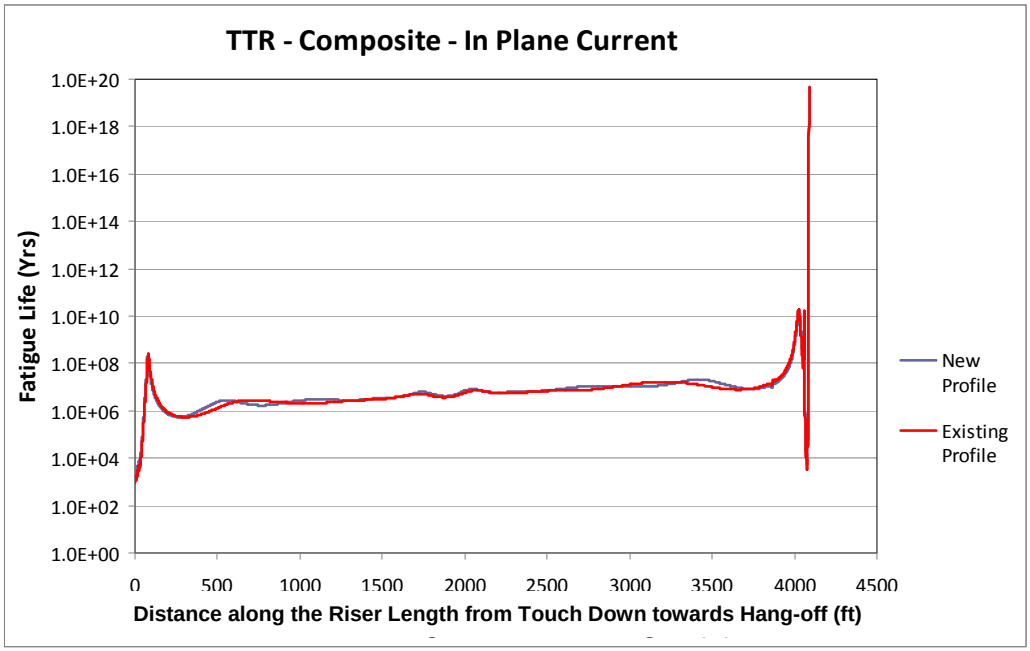

Figure 4-11: Comparison between VIV fatigue damages caused by existing and new profiles (Zone = 2, Water Depth=4,000ft, Event = Extreme, VIV type = In-plane, Riser Type = TTR)

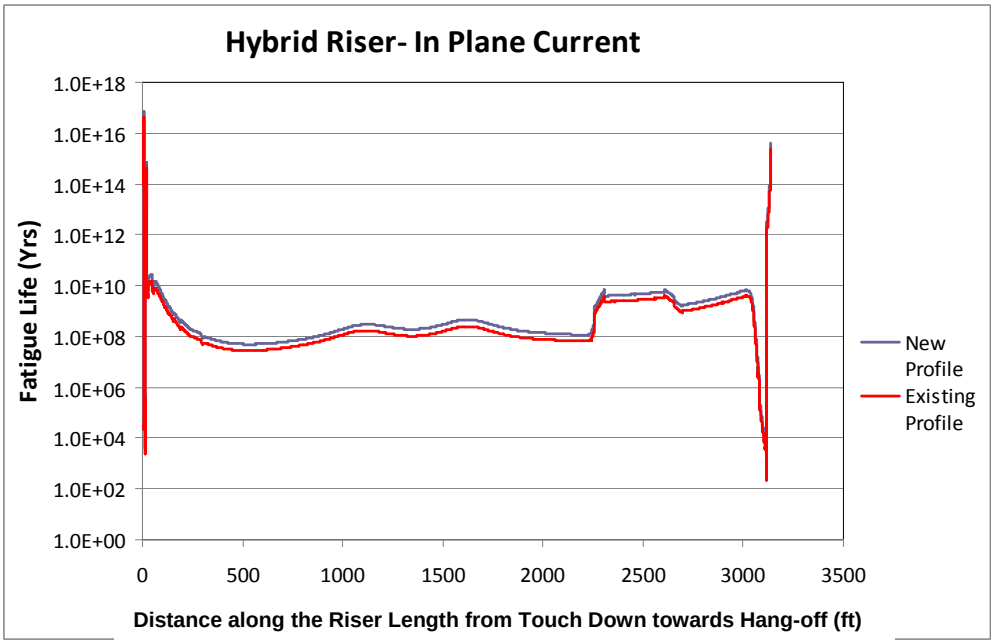

Figure 4-12: Comparison between VIV fatigue damages caused by existing and new profiles (Zone = 2, Water Depth=4,000ft, Event = Extreme, VIV type = In-plane, Riser Type = Hybrid Riser)

Extreme event fatigue life in terms of years, damage rate per year and percent different in damage between the Existing and New current profiles for each riser type is provided in Table 4-4.

Table 4-4: Extreme Event In-Place Damage Assessment Calculation for all Riser Types for Zone 2

Water Depth (ft)	Riser Type	Fatigue Life (yrs)		Damage Rate		% Difference in Damage between Existing and New Current Profiles
		Existing	New	Existing	New	
4,000 ft	SCR	22.4	27.6	0.044518/yr	0.036178/yr	+23.05%
	Tendon	1.87E+07	2.53E+07	5.34E-08/yr	3.95E-08/yr	+35.19%
	Drilling Riser	47.75	79.2	0.020942/yr	0.012619/yr	+65.95%
	TTR	951.7	1486.8	0.001051/yr	0.000673/yr	+56.23%
	Hybrid	204.82	336.15	0.004882/yr	0.002975/yr	+64.11%

4.3 STEP 3: Zone Study

Step 3 assessed the impact of various zones in the GoM on the VIV fatigue life difference between the new and the existing current profiles. The study was performed for three zones in the GoM, namely, Zone1, Zone 2 and Zone 3. The TTR-composite riser and the hybrid riser were chosen to perform the analysis on.

Again, all the other parameters were kept constant.

4.1.5 Long Term Event

Figure 4-13 and Figure 4-15 shows fatigue damage for a TTR-composite riser at 4,000 ft for Zone 1 and Zone 3, respectively. Similarly, Figure 4-14 and Figure 4-16 shows fatigue damage for a hybrid riser at 4,000 ft for Zone 1 and Zone 3, respectively. Results for Zone 2 are presented in section 4.2.

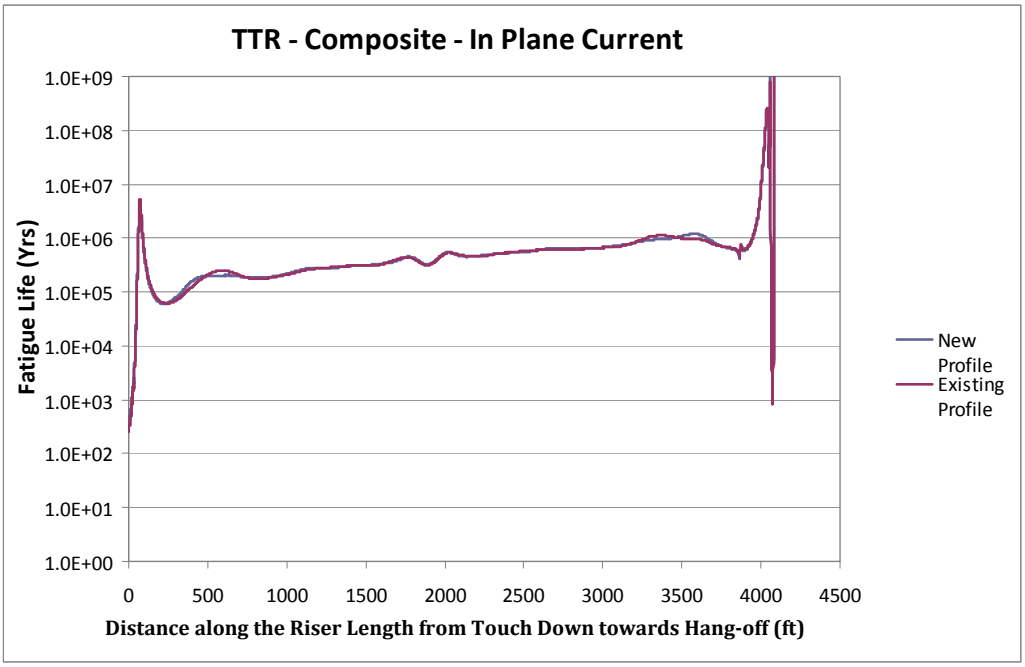

Figure 4-13: Comparison between VIV fatigue damages caused by existing and new profiles (Zone = 1, Water Depth=4,000ft, Event = Long-term, VIV type = In-plane, Riser Type = TTR)

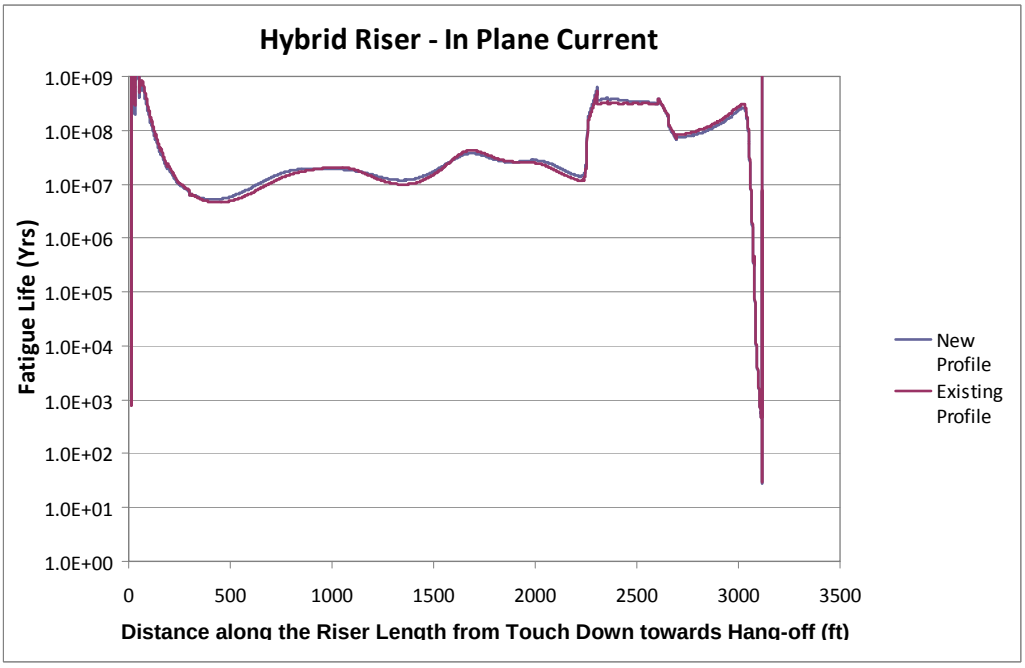

Figure 4-14: Comparison between VIV fatigue damages caused by existing and new profiles (Zone = 1, Water Depth=4,000ft, Event = Long-term, VIV type = In-plane, Riser Type = Hybrid Riser)

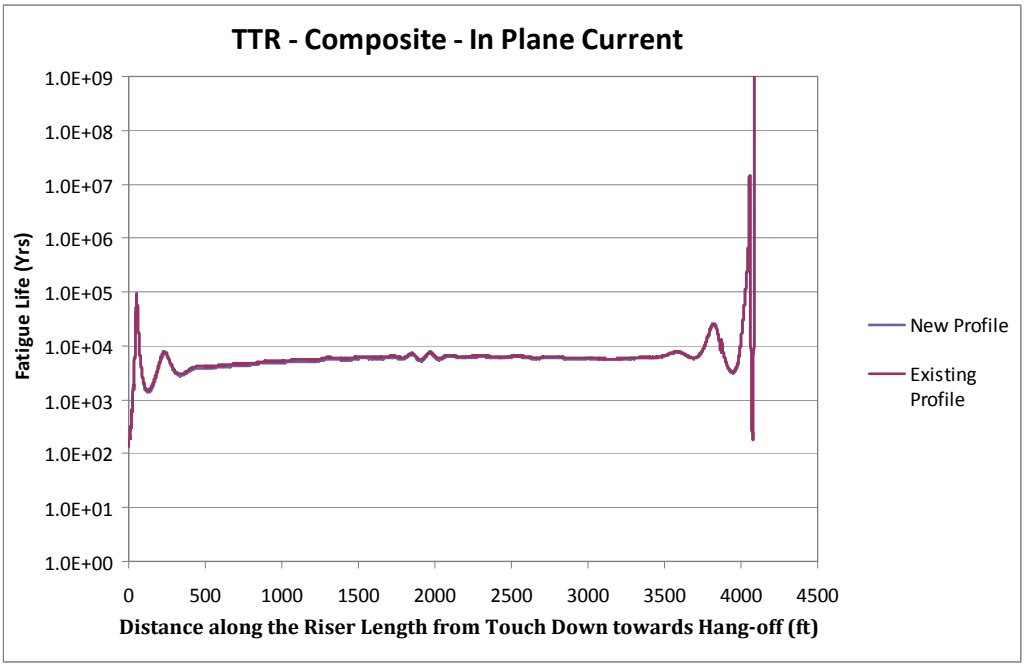

Figure 4-15: Comparison between VIV fatigue damages caused by existing and new profiles (Zone = 3, Water Depth=4,000ft, Event = Long-term, VIV type = In-plane, Riser Type = TTR)

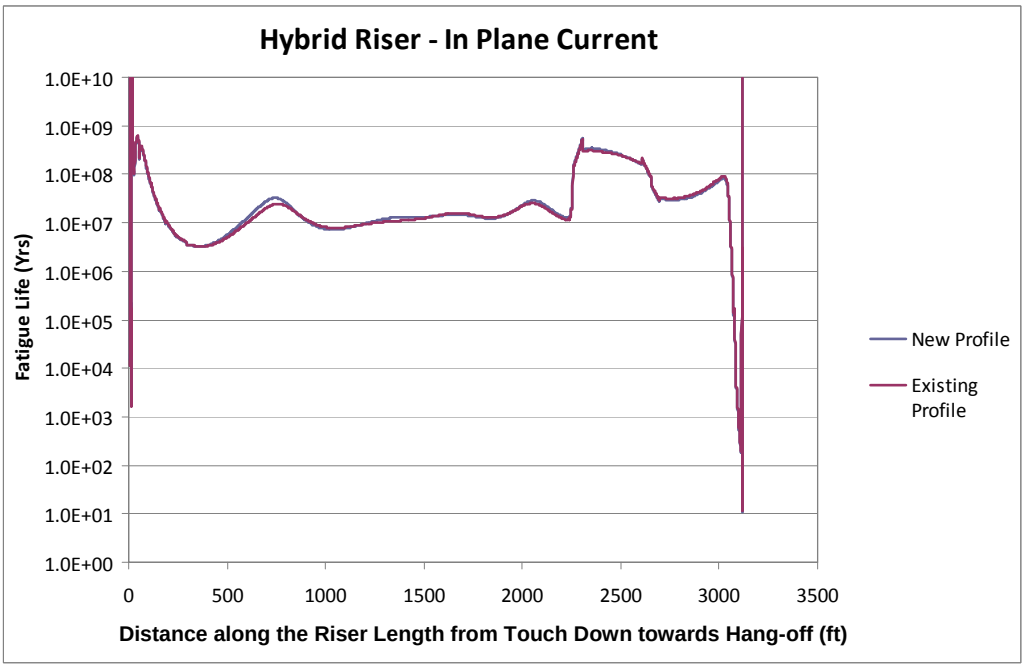

Figure 4-16: Comparison between VIV fatigue damages caused by existing and new profiles (Zone = 3, Water Depth=4,000ft, Event = Long-term, VIV type = In-plane, Riser Type = Drilling Riser)

Table 4-5 presents the damage calculations for the TTR-composite riser and the Hybrid riser for Zone 1, 2 and 3.

Table 4-5: Long-term Damage Assessment Calculation for TTR and Hybrid Riser

Zone	Riser Type	Fatigue Life (yrs)		Damage Rate		% Difference between Existing and New Current Profiles
		Existing	New	Existing	New	
Zone 1	TTR-Composite	257.7	319	0.003879/yr	0.003135/yr	+19.2%
	Hybrid	29.6	28.6	0.033698/yr	0.034908/yr	-3.59%
Zone 2	TTR-Composite	308	297	0.003/yr	0.003/yr	-3.4%
	Hybrid	45.5	39.5	0.022/yr	0.025/yr	-13.0%
Zone 3	TTR-Composite	133.2	132.6	0.007506/yr	0.007541/yr	-0.5%
	Hybrid	12	11	0.0841/yr	0.09132/yr	-7.9%

4.1.6 Extreme Event VIV Fatigue Analysis

Figure 4-17 and Figure 4-19 shows extreme events VIV fatigue damage for a TTR-composite riser at 4,000 ft for Zone 1 and Zone 3, respectively. Similarly, Figure 4-18 and Figure 4-20 shows fatigue damage for a hybrid riser at 4,000 ft for Zone 1 and Zone 3, respectively. Results for Zone 2 are presented in section 4.2.

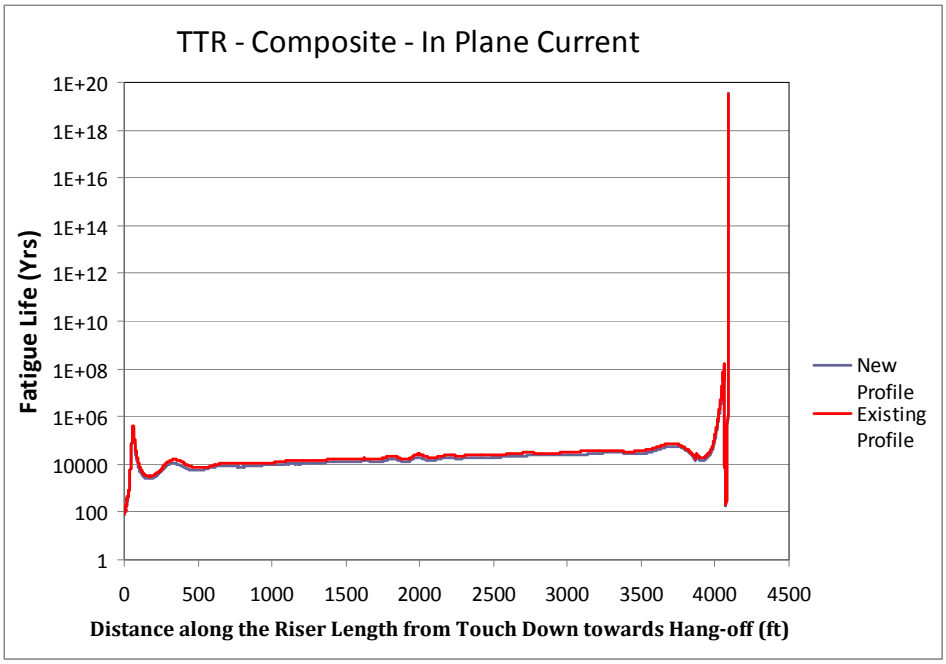

Figure 4-17: Comparison between VIV fatigue damages caused by existing and new profiles (Zone = 1, Water Depth=4,000ft, Event = Extreme, VIV type = In-plane, Riser Type = TTR)

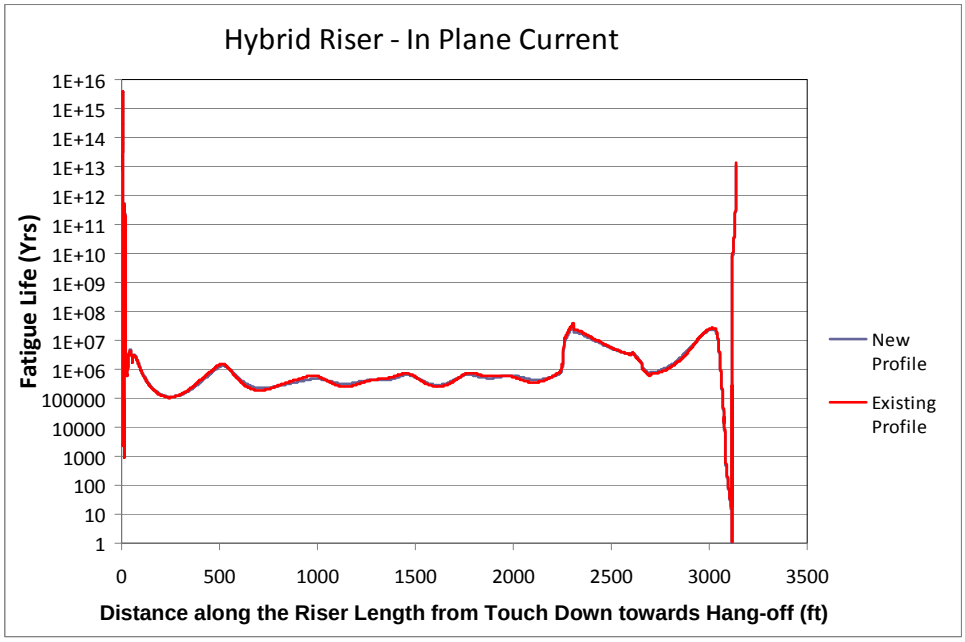

Figure 4-18: Comparison between VIV fatigue damages caused by existing and new profiles (Zone = 1, Water Depth=4,000ft, Event = Extreme, VIV type = In-plane, Riser Type = Hybrid Riser)

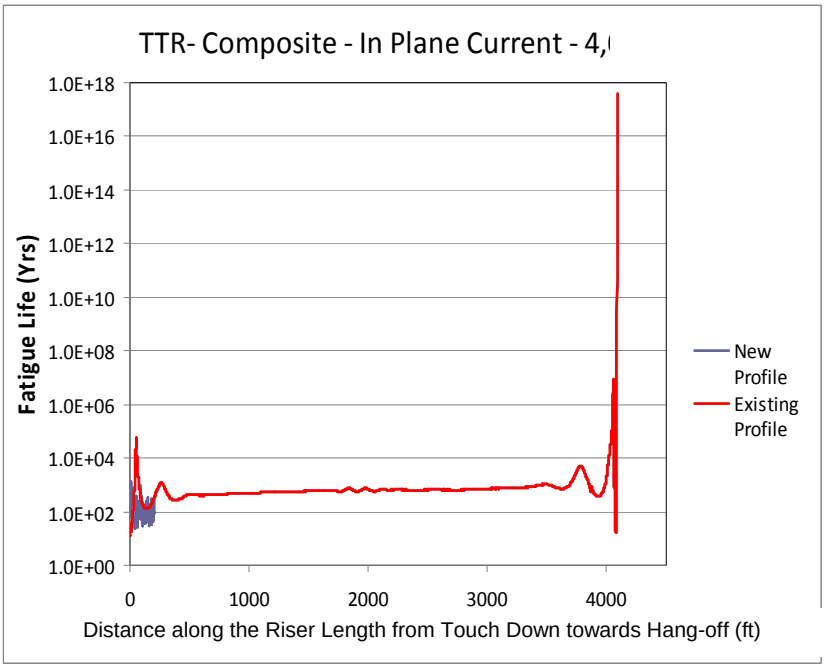

Figure 4-19: Comparison between VIV fatigue damages caused by existing and new profiles (Zone = 3, Water Depth=4,000ft, Event = Extreme, VIV type = In-plane, Riser Type = TTR)

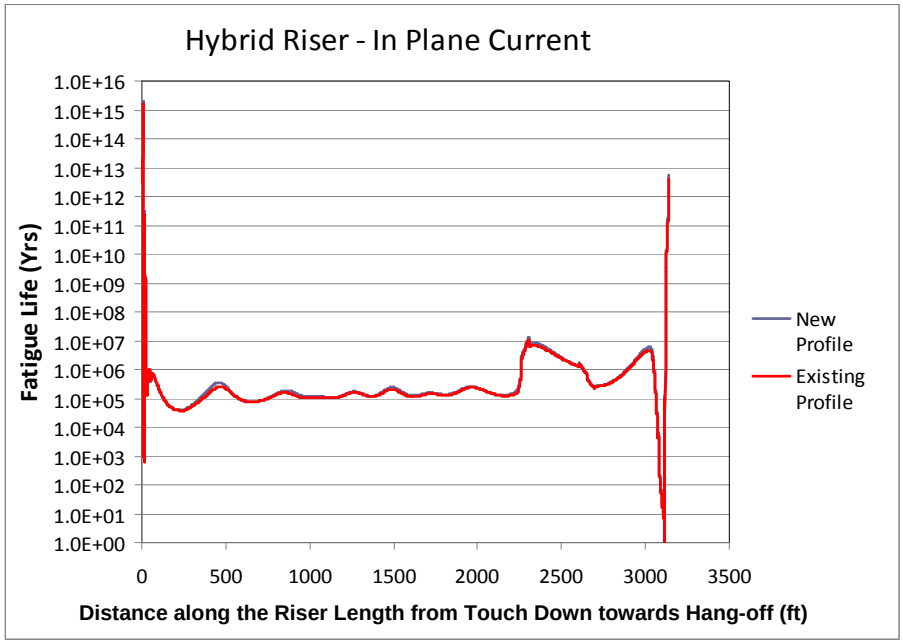

Figure 4-20: Comparison between VIV fatigue damages caused by existing and new profiles (Zone = 3, Water Depth=4,000ft, Event = Extreme, VIV type = In-plane, Riser Type = Hybrid Riser)

Table 4-6 presents the extreme event damage calculations for the TTR-composite riser and the Hybrid riser for Zone 1, 2 and 3.

Table 4-6: Extreme Event Damage Assessment Calculation for TTR and Hybrid Riser

Zone	Riser Type	Fatigue Life (yrs)		Damage Rate		% Difference between Existing and New Current Profiles
		Existing	New	Existing	New	
Zone 1	TTR-Composite	85	74	0.01174/Yr	0.01343/yr	-12.6%
	Hybrid	1.1	0.97	0.903363/Yr	1.027906/yr	-12.1%
Zone 2	TTR-Composite	951.7	1486.8	0.001051/yr	0.000673/yr	+56.23%
	Hybrid	204.82	336.15	0.004882/yr	0.002975/yr	+64.11%
Zone 3	TTR-Composite	13	16	0.075054/Yr	0.058989/yr	+27.23%
	Hybrid	0.348	0.449	2.866862/yr	2.223965/yr	+28.9%

5.0 CONCLUSIONS

Results of the analyses and MCS Kenny's opinion, based on the results, are documented in this report for BOEMRE to assess and conclude regarding the significance of the difference between the VIV fatigue damage under either of the current profiles, and consequently, on the requirement regarding monitoring of the current between 500 and 1,000 meters in the GoM.

MCS Kenny has the following opinion based on the results of the performed detailed VIV analyses:

6. The difference between fatigue life estimates based on the two (existing & new) profiles of long-term current events is not significant. Therefore, monitoring of long term current events between water depths of 500 - 1,000 m is not needed;
7. The difference between fatigue life estimates based on the two (existing & new) profiles of short-term current events is also not needed, if the probabilistic distribution of extreme current events is utilized for calculating the riser fatigue life;
8. The difference between fatigue life estimates based on the two (existing & new) is observed for the extreme events, if a single current event is utilized to obtain the fatigue life estimation, as shown in Appendices. The single extreme current event assumption is nonetheless particularly conservative and should be avoided.

6.0 REFERENCES

9. Vukovich, F.M., 2005. Climatology of Ocean Features in the Gulf of Mexico: Final Report. U.S. Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, LA. OCS Study MMS 2005-031 58 pp.
10. Fugro, BOEMRE TA&R Program on Safety Oil and Gas Operations in the US OCS Ocean Current Monitoring from 500-1,000 meters.

APPENDIX A:

VIV FATIGUE UNDER EXTREME EVENT ASSUMING SINGLE PROFILE - ZONE 1

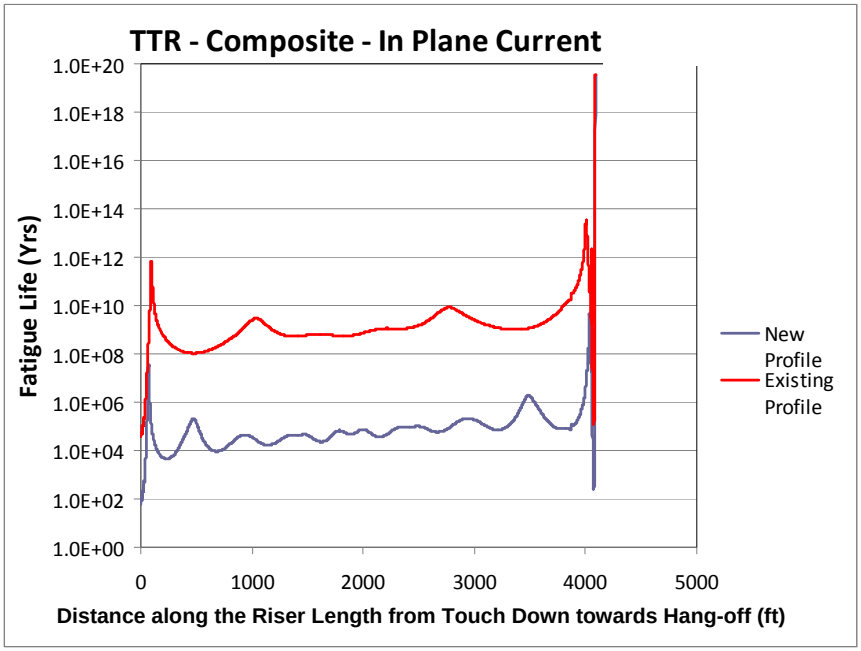

Figure A - 1: Comparison between VIV fatigue damages caused by existing and new profiles (Zone = 1, Water Depth=4,000ft, Event = Long-term, VIV type = In-plane, Riser Type = TTR)

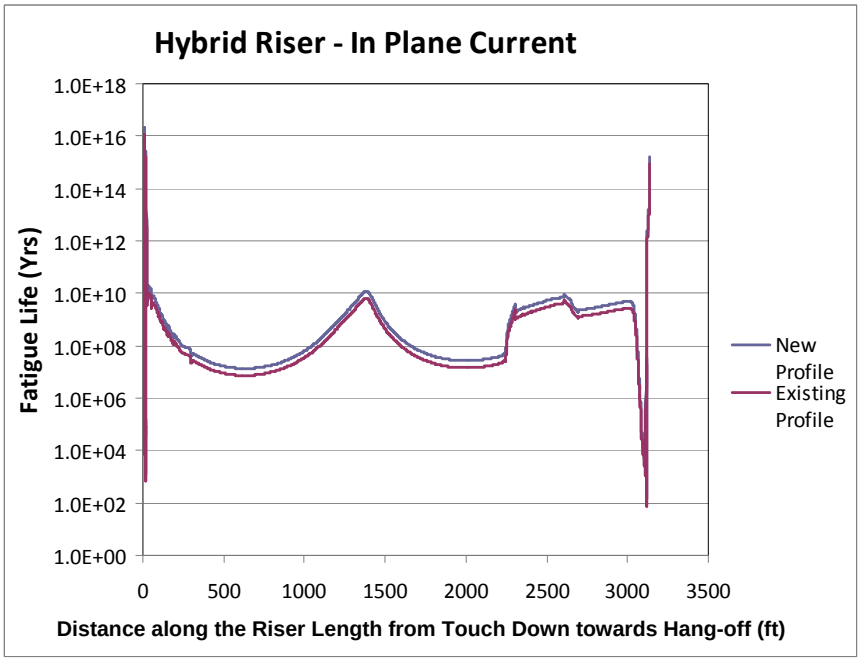

Figure A - 2: Comparison between VIV fatigue damages caused by existing and new profiles (Zone = 1, Water Depth=4,000ft, Event = Long-term, VIV type = In-plane, Riser Type = Hybrid Riser)

APPENDIX B:

VIV FATIGUE UNDER EXTREME EVENT ASSUMING SINGLE PROFILE - ZONE 2

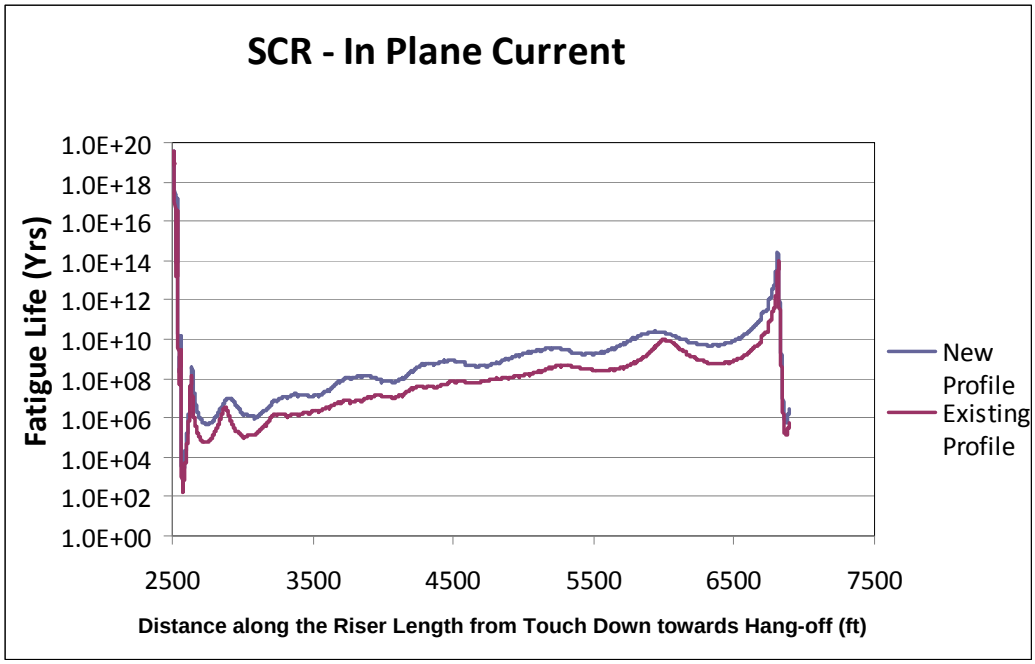

Figure B - 1: Comparison between VIV fatigue damages caused by existing and new profiles (Zone = 2, Water Depth=4,000ft, Event = Extreme, VIV type = In-plane, Riser Type = SCR)

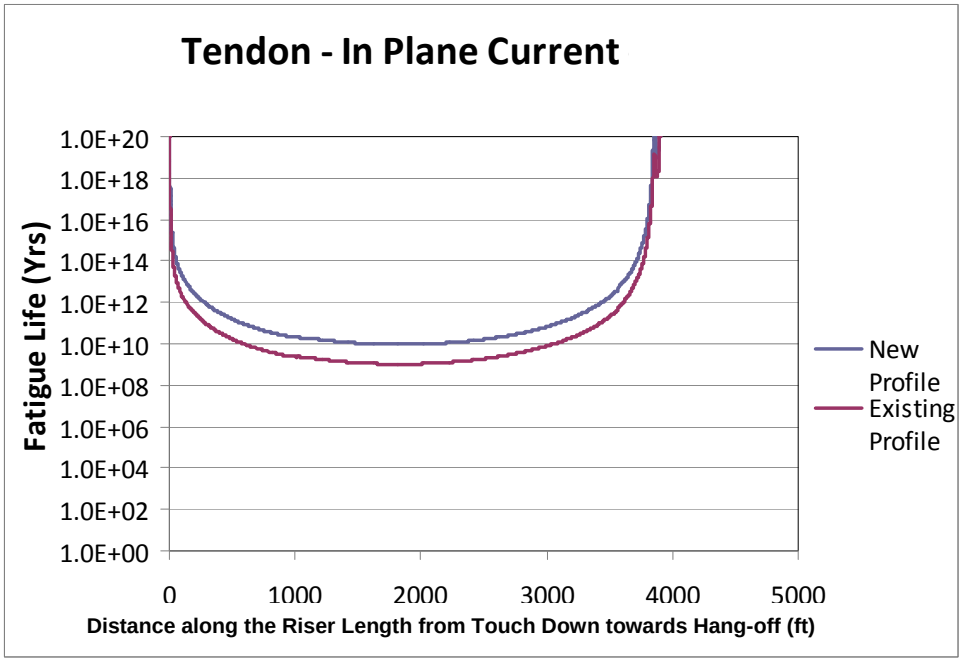

Figure B - 2: Comparison between VIV fatigue damages caused by existing and new profiles (Zone = 2, Water Depth=4,000ft, Event = Extreme, VIV type = In-plane, Type = Tendon)

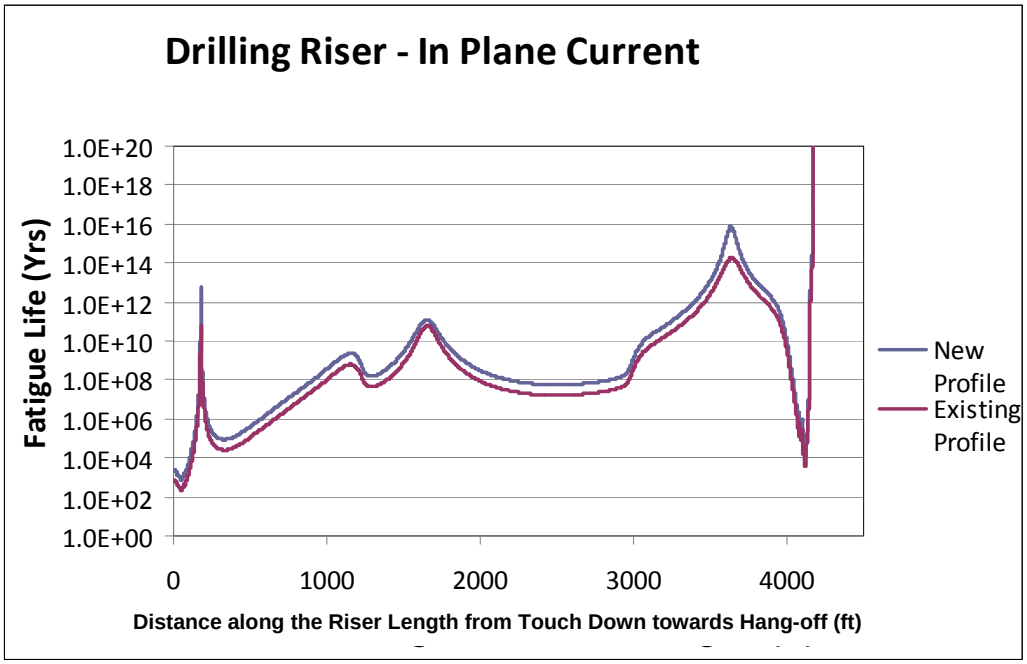

Figure B - 3: Comparison between VIV fatigue damages caused by existing and new profiles (Zone = 2, Water Depth=4,000ft, Event = Extreme, VIV type = In-plane, Riser Type = Drilling Riser)

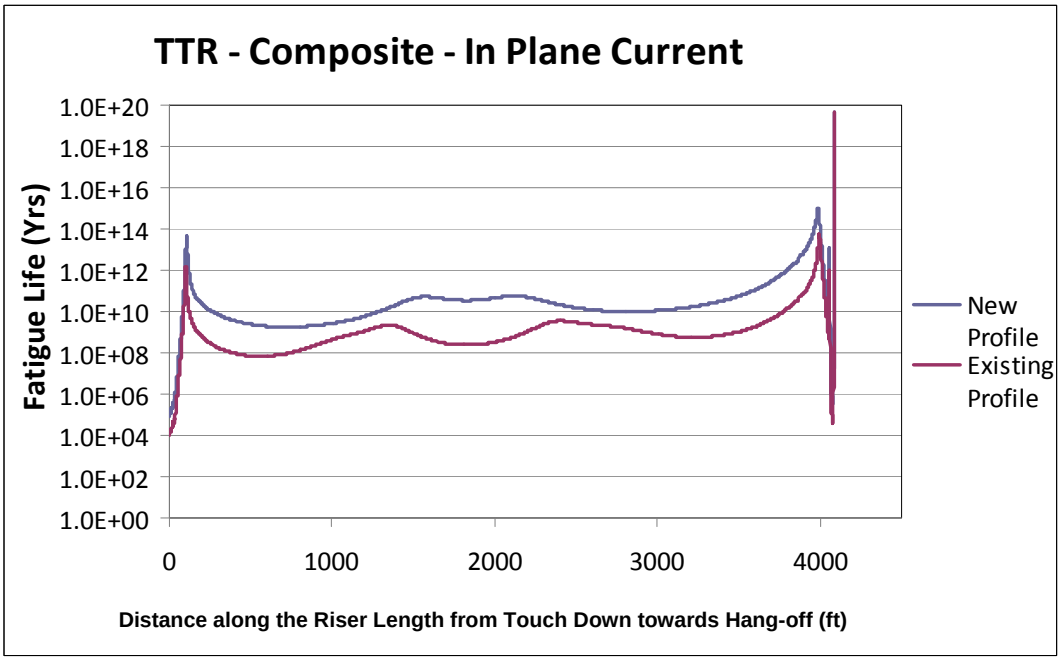

Figure B - 4: Comparison between VIV fatigue damages caused by existing and new profiles (Zone = 2, Water Depth=4,000ft, Event = Extreme, VIV type = In-plane, Riser Type = TTR)

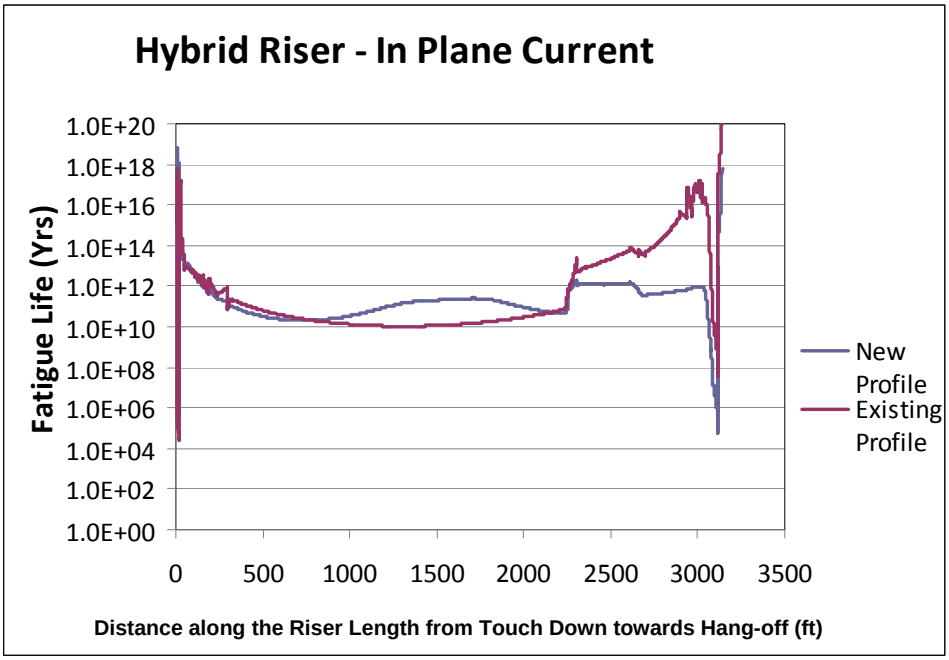

Figure B - 5: Extreme event comparison between In-plane VIV Fatigue damage for Hybrid Riser with Existing and New Current profile for Zone 2

APPENDIX C:

VIV FATIGUE UNDER EXTREME EVENT ASSUMING SINGLE PROFILE - ZONE 3

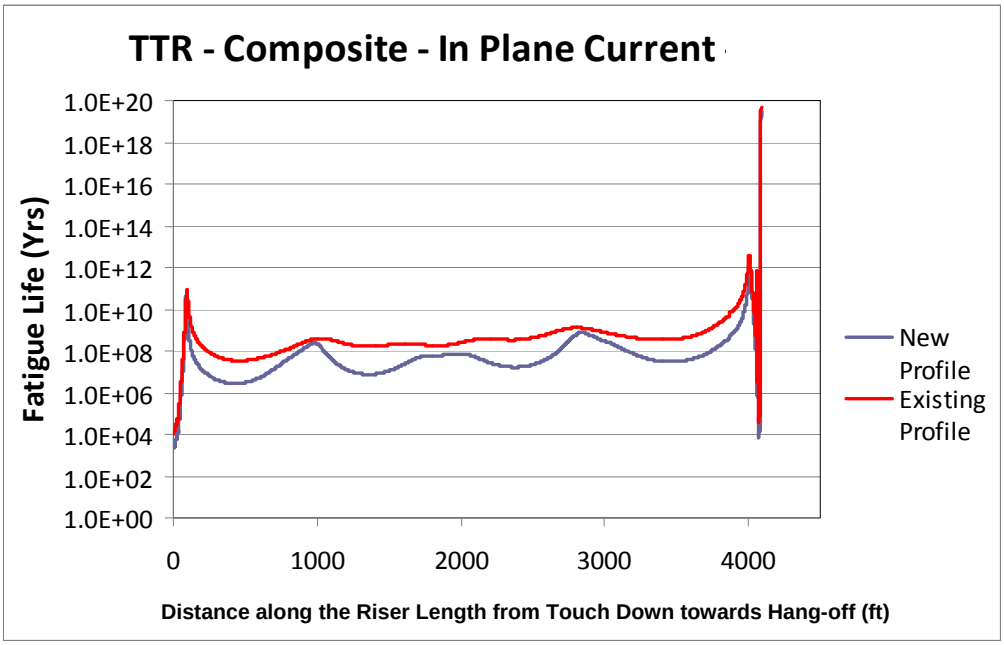

Figure C- 1: Comparison between VIV fatigue damages caused by existing and new profiles (Zone = 3, Water Depth=4,000ft, Event = Extreme, VIV type = In-plane, Riser Type = TTR)

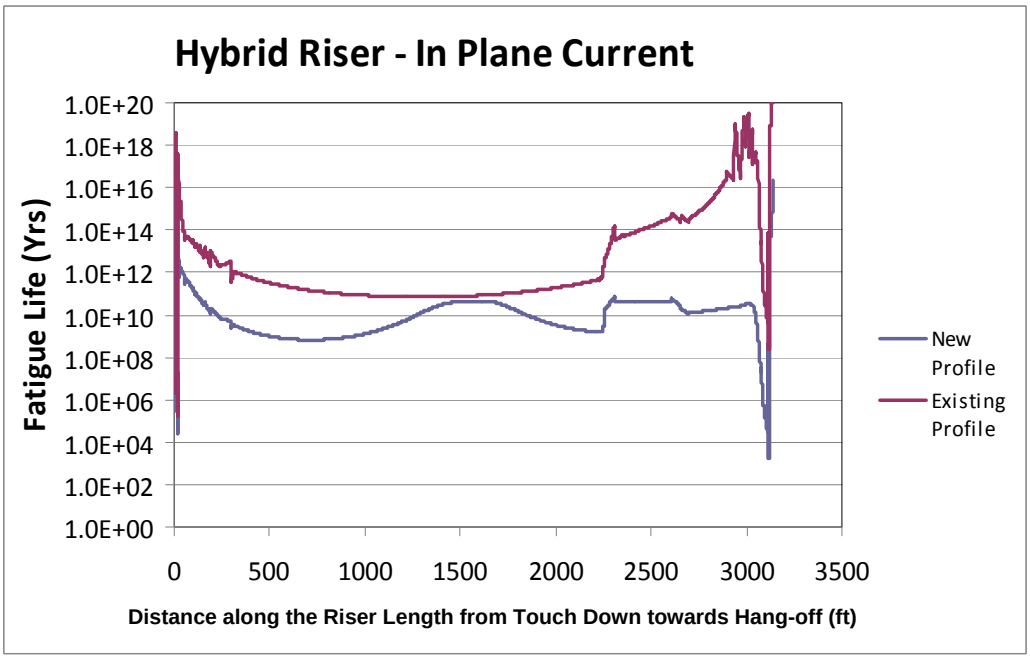

Figure C- 2: Comparison between VIV fatigue damages caused by existing and new profiles (Zone = 3, Water Depth=4,000ft, Event = Extreme, VIV type = In-plane, Riser Type = Hybrid Riser)