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Design and Regulatory Considerations of SPAR Buoy based Floating Production System

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Design and Regulatory Considerations of SPAR Buoy based Floating Production System

INTRODUCTION

During the last two decades, the offshore industry successfully met the challenge of installation of offshore platforms in deep water for oil production. The definition of deep water has changed a few times. Currently water depth of 2,000 feet and beyond is referred to as deep water. Five (5) tension leg platforms, e.g., Hutton (480 feet W.D. in UK), Jolliet (1750 feet in GOM), Snorre (1020 feet in Norway), Auger (2850 feet in GOM), and Heidrun (1130 feet in Norway) have already been installed. It is to be noted that only Shell Auger TLP has been installed in "deep water" defined as above. Two more TLPs, Mars in water depth of 2933 feet and Ram Powell in water depth of 3220 feet are being planned for installation in the Gulf of Mexico.

Many innovative and cost effective mooring systems e.g., single point (weathervaning) mooring system, deep water mooring systems with spring buoy and appropriate combinations of mooring line segments, and tension legs as shown in Figure 1 have made it possible to explore oil offshore. For deep water oil field development, consideration of utilizing the concept of TLP comes almost naturally to the designer and operator. Nevertheless, the concept of TLP has been considered by many industry experts to be expensive. As the oil price remains depressed, operators and designers are continually studying other alternatives such as a SPAR buoy based FPS. The concept of a SPAR buoy appears to be very promising because it offers a substantial cost advantage over a TLP. This concept is new and has not been installed yet as an FPS in deep water. Oryx Energy and CNG Producing Company already approved of fabrication of one such design, and is expected to be installed in 1996 in the Gulf of Mexico in a water depth of 1930 feet.

DESCRIPTION

A SPAR buoy based FPS, as presented in Figure 2, consists of four key elements, e.g., hull, deck, mooring, and the riser system. This concept is unique because of the configuration of the hull, the other three elements are very similar to that of a semisubmersible based FPS.

Hull and Deck

The SPAR is a large diameter (60-140 feet), deep draft (500-800 feet) cylindrical floating caisson (Figure 2), designed not only to support production equipment, but if required, to support drilling operations as well. The risers for such a system run up the hull through a large center well along the length of the hull structure. The risers are thus very well shielded from the dominant wave action. The buoyancy to support the equipment, accommodations, and systems required for production and/or drilling operations is provided by watertight compartments (or hard tanks) in the top (200-300) feet of the hull structure. Soft tanks are usually provided for buoyancy requirement during tow out from the fabrication yard to the installation site and also for ballasting during various marine operations including the upending. A design may require the provision of fixed ballast near the keel of the SPAR.

The SPAR hull is fitted with appurtenances such as boat landings, barge bumpers, anode attachments, walk ways, hand rails, stairs, etc. It is found that a SPAR hull is likely to be subjected to vortex induced vibration (VIV) and should be fitted with strakes to suppress the VIV.

The cellar deck located at the top of the SPAR hull, provides the space for the mooring winches, and storage of the BOP stack. The Christmas trees may be located at the cellar deck level and are connected to production manifolds with flexible hoses.

The deck to accommodate the production system, the work over area, and the quarters for personnel onboard is located over the SPAR hull. The deck structure may be designed either as a plate girder or truss structure. The deck structure is also fitted with appurtenances such as stairs, hand rails, crane pedestal, drains, scaffold supports, etc.

Mooring System

The mooring system for keeping the SPAR based FPS on location is generally designed as a conventional catenary (or spread) mooring system as shown in Figure 3(a). The conventional system with long mooring lines in deep water can be quite expensive. Alternative arrangement using taut mooring system requiring lesser mooring line length, and smaller foot print of the anchoring location has also been designed and is presented in Figure 3(b). It is claimed that the cost of such taut mooring system is substantially lower that of a conventional system.

The anchoring system be designed either as a pile or as a drag embedded anchors with high holding capacity. It is generally felt by the designers that though the pile driven anchoring system is more reliable, the drag embedded anchor may be more cost effective design. There are a few on-going projects where the high holding capacity anchors will be deployed very soon. For a taut mooring system, the anchoring system with driven piles is preferable because of the reliability and confidence level of pile design.

It may be noted that recent large scale anchor tests in the Gulf of Mexico (GOM) confirm that the high holding capacity anchors are capable of resisting large uplift forces in typical GOM soil condition. It is envisioned that future mooring design in GOM deep water will be taking advantage of this characteristic of high holding capacity anchors.

Production Facilities

The production equipment is laid out on the deck consisting of two or more levels. The design of the facilities is similar to that of any fixed production platform. Since the production facilities have not been the focal interest of this JIP, they are not elaborated here in this document.

PERFORMANCE

The wave induced motion of a SPAR based floating production system is found to be superior to that of the other conventional floating system using tankers or column stabilized (semisubmersible) units. The motion responses in waves are considerably less, primarily because of the massiveness of the structure. The entrapped mass of water inside the hull, along with the added mass act as the mass of the dynamic system resulting in very high system natural periods. The natural periods of a SPAR based platform are compared below with those of a TLP:

	SPAR	TLP	
Heave	28 - 29	3 - 6	seconds
Roll/ Pitch	60 - 80	3 - 6	seconds
Surge/ Sway	300 -350 100 -200 *	70 -120	seconds

* *at mean offset condition with 100 year storm*

It is to be noted that the natural periods of a SPAR based FPS are well beyond the dominant range of wave energy of various sea states, and since the only body which is subjected to this energy is the large cylindrical hull, the wave exciting forces are not large enough to cause any large dynamic first order responses. The wind and current forces contribute significantly to the excursion in the horizontal plane, i.e, surge and sway components of the responses.

DESIGN CONSIDERATIONS

The design of a SPAR based Floating Production System is governed by the normal requirements of any other floating platforms, such as, operational, functional, safety of life and environment. The process equipment is designed to meet the required production rates of oil and gas. The platform buoyancy should be adequate to support production equipment, deck structure with appurtenances, ballast, riser tension at the deck level, and the hull structure including marine systems and appurtenances. The mooring system design is to meet the operational limitations of platform excursion, maximum allowable mooring line load at extreme environmental condition, target fatigue life, etc.

Though it is not possible to identify all the design considerations for a system such as the SPAR based FPS, the key design areas may be identified as follows:

- Environmental Loads and Criteria
- Mooring Analysis and Design
- Anchor Design
- Structural Design - Hull and Deck

The above design areas are described here with reference to the design of SPAR based floating production systems. Since there are not any floating production platforms which have been designed using this concept of a SPAR, rules and standards specific to the design of such platform are not available. It is necessary that design of such a system be carried out using relevant requirements of existing rules and standards for ships, floating production system, and other offhsore structures. Other SPAR based systems such as offloading/storage structures were built to available rules and standards for designing Ships, Single Point Mooring and Offshore Loading Systems with modifications as appropriate to their design.

Environmental Conditions

The environmental conditions to which a floating production system may be exposed during its life are to be described using adequate data for the specific site of operation. It is very likely that a SPAR hull (700-800) feet long will be built in two pieces at some location, towed dry in a transporting vessel to a suitable location for joining them into one piece, then towed wet to the site of installation. Nevertheless, it is conceivable that the entire hull can be fabricated in one piece for wet or dry tow as an unit. The hull will then be upended and moored prior to the mating of deck to the hull. For various stages of the marine operations, design environmental conditions are to be established with proper consideration of duration of exposure, contingency plan, and the consequences of mishaps if any.

The environmental phenomena which may influence the design or operation of the installation are to be described in terms of the characteristic parameters which are most relevant in the evaluation of their effects on the installation and operations. Statistical data and realistic statistical and mathematical models which describe the range of pertinent expected variations of environmental conditions are to be employed.

Probabilistic methods for short-term, long-term and extreme-value prediction are to employ statistical distributions appropriate to the environmental phenomena being considered, as evidenced by relevant statistical tests, confidence limits and other measures of statistical significance.

Environmental Loading

In general, the design of a SPAR based floating production system will require investigation of the following environmental parameters mainly for determining the design load of its mooring or station keeping system:

Currents

Wind
Waves
Marine growth
Tides and storm surges
Air and sea temperatures

Current

The current forces on the submerged hull, mooring lines (especially in deep water), risers or any other submerged objects associated with the system are to be calculated.

Current force $F_{current}$ in Kg (lbs) on the submerged part of any structure is normally calculated as the drag force by the following equation:

$$F_{current} = \tfrac{1}{2} \times \rho_{water} \times C_D \times A_{current} \times u_c \times |u_c|$$

where:
- ρ_{water} = density of water in $N\text{-}s^2/m^4$ ($lb\text{-}s^2/ft^4$)
- C_D = drag coefficient, in steady flow (dimensionless)
- u_c = component of current velocity vector normal to the plane of projected area in m/s (ft/s)
- $A_{current}$ = projected area exposed to current in m^2 (ft^2)

The drag coefficient C_D for the cylindrical submerged hull should not be taken less than 1.00, unless a reliable value is obtained from some other sources such as model tests. For a hull fitted with strakes for suppressing vortex induced vibration, the designer should take into account of the current forces (i.e., the drag force) on the strakes. The designer should consider the effective diameter of the SPAR hull as the diameter of the SPAR hull plus twice the width of the attached strake. The drag forces due to the appurtenances fitted external to the hull should also be taken into account.

Since the SPAR is subjected to Vortex Induced Motions (VIV), its mean drag coefficient will be affected by the amplitude of oscillation *(Ref: Blevins, R.D., Flow Induced Vibration, Van Nostrand Reinhold, N.Y., 2nd edition, 1990 - see Section 3.3)*. Model tests should be used to verify the amount of VIV and the effect on the mean drag coefficient with or without vortex suppression devices.

Wind

The wind force on a floating production system is very important for the design of station keeping system and assessing the stability of the floating vessel. The wind speeds for various design conditions are to be established from collected wind data and should be consistent with other environmental parameters assumed to occur simultaneously. Wind speed should be based on a recurrence period of 100 years.

The environmental report pertaining to wind is to present wind statistics for the site of installation, and for the transportation route. It is to include a wind rose or table showing the frequency distribution of wind velocity and direction and a table or graph showing the recurrence period of extreme winds.

Wind Load

Wind pressure on a floating vessel may be calculated as drag forces using the following equations:

$$p_{wind} = 0.0623 \times C_h \times C_s \times V_{wind}^2 \ \text{kg/m}^2, \quad \underline{for}\ V_{wind} \textit{ in m/s}$$
$$= 0.00338 \times C_h \times C_s \times V_{wind}^2 \ \text{lb/ft}^2, \quad \underline{for}\ V_{wind} \textit{ in knots}$$

p_{wind} = Wind pressure in kg/m^2 (lb/ft^2)
C_h = Height Coefficient (dimensionless)
C_s = Shape Coefficient (dimensionless)
V_{wind} = Velocity (one-minute average) of wind at an elevation of 10 m (33 feet) in m/s (knot); or one-hour average wind plus a time-varying component calculated from a suitable wind gust spectrum

The height coefficients C_h to represent the wind velocity profile are presented in Table 1 for height interval of 50 feet. These values are derived by the following equation:

$$C_h = (V_z / V_{ref})^2$$

where, the velocity of wind V_z at a height z is to be calculated as follows:

$$V_z = V_{ref} \times (z / Z_{ref})^{\beta}$$

V_{ref} = Velocity of wind at an reference height Z_{ref} of 10 m (33 feet)

β = 0.10 for one-minute average wind
0.125 for one hour average wind. A time-varying component calculated from a suitable wind gust spectrum is to be added to the wind force using one-hour average wind.

The shape coefficients for typical structural shapes are presented in Table 2. To convert the wind velocity V_t at a reference height of 10 m (or 33 feet) for a given time average *"t"* to velocity of another time average, the following relationship is to be used:

$$V_t = f \times V_{(1\text{-}hr)}; \quad \text{where factor "}f\text{" is quoted in Table 3.}$$

The wind force F_{wind} is to be calculated as follows:

$$F_{wind} = p_{wind} \times A_{wind};$$

where, A_{wind} = Projected area of windage on a plane normal to the direction of wind, in m^2 (ft^2)

For describing the wind velocity profile, the windages are to be divided into panels of 50 feet high in the vertical plane. The summation of wind forces in each panel will give the total wind force. Alternatively, the total force on a given windage can be determined by determining the wind force on an infinitesimal area first, and then integrating over the whole area. Wind forces can be more reliably obtained by wind tunnel tests.

Wind tunnel test to determine the wind loading for the final configuration is strongly recommended. Proper test procedures should be employed to account for turbulence and wind profile. The designer should refer to "Guidelines for Wind Tunnel Testing of Mobile Offshore Drilling Units, Technical & Research Bulletin 5-4, 1988, a publication of Society of Naval Architects and Marine Engineers.

When the designer is provided with information regarding the wind spectrum, the wind force on the vessel can be calculated as outlined API RP 2T Section 3.2. The wind force consists of two parts, steady component based on 1-hr. average wind velocity and a time-varying component based on the wind energy spectrum. It may be noted that when there is lack of confidence in deriving the energy spectrum, the approach of wind force as constant is more desirable.

Table 1

Height Coefficients for Windages

Height of Center of Pressure above Water Line

Height above Water Line		for Wind Profile with β = 0.10	
Meters	Feet	1-min	1-hr
0 - 50	0 - 15.3	1.00	1.00
50 - 100	15.3 - 30.5	1.18	1.23
100 - 150	30.5 - 46.0	1.31	1.40
150 - 200	46.0 - 61.0	1.40	1.52
200 - 250	61.0 - 76.0	1.47	1.62

Table 2

Shape Coefficients for Windages

Cylindrical Shapes		0.70-1.00 *
Hull above waterline		1.00
Deck House		1.00
Isolated structural shapes (Cranes, channels, beams, angles, etc.)		1.50
Under deck areas (smooth)		1.00
Under deck areas (exposed beams and girders)		1.30
Rig derrick	*(each face* **)	1.25
Mooring Chains	(¶)	
Mooring Wire Ropes	(¶)	1.00

* *Use a minimum of 1.00 for the SPAR hull.*

** *30% of projected block areas for both front and back sides*

¶ *recommended values of drag coefficients for calculating current forces*

Table 3

Wind Velocity (§) Time Average Conversion Factor

Time Period	factor *"f"*
1 Hour	1.000
10 Min	1.060
1 Min	1.180
15 Sec	1.260
5 Sec	1.310
3 Sec	1.330

§ *Wind Velocity at Reference Height of 10 m (or 33 feet)*

Waves

Wave criteria specified by the Owner may be described by means of wave energy spectra, wave height and associated period for the location at which the unit is to operate. Waves are to be considered as coming from any direction relative to the unit. The directionality of waves may be considered in the design if a detailed environmental report is available for the specific site. Consideration is to be given to waves other than waves of maximum height, because the wave induced motion responses for waves with certain periods may be larger in some cases due to the dynamic behavior of the system as a whole.

Wave Forces

The wave forces acting on a SPAR based floating platform are considered to consist of three components, e.g., first order forces at wave frequencies, second order forces at frequencies lower than the wave frequencies, and a steady component of the second order forces. The calculations of wave loading are necessary for assessing the vessel motion responses and the mooring system. This requires calculations of hydrodynamic loading and characteristics of the SPAR for a given environmental condition. The calculations are to be based on acceptable methods such as Morrison's equation, diffraction theory, model tests or full scale measurements.

For calculations of wave loads on structural configurations which significantly alter the incident wave field, diffraction methods are recommended for taking into account both the incident wave force (i.e. Froude-Krylov force) and the forces resulting from wave diffraction and radiation. Application of Morison's equation may not be accurate for the SPAR with diameter as large as (60-80) feet unless modified and calibrated with model test data, particularly for determination of operation responses.

Wave induced Vessel Motion Responses

The wave induced motion responses of the SPAR are very important for mooring system design. The wave induced responses of a floating platform basically consist of three categories of response, e.g., first order (wave frequency) motion, low frequency or slowly varying motions, and steady drift.

a. **First Order Motions** These motions have six degrees of freedom (surge, sway, heave, roll, pitch and yaw) and are at wave frequencies which can be obtained from model test in regular or random waves, or by computer analysis in frequency or time domain.

b. **Low Frequency Motions** These motions are induced by low frequency components of second order wave forces any by wind gust forces.

The SPAR responds to both first and second order forces in distinct modes which are unique to the SPAR's deep draft. first order wave forces act near the free surface and result in larger first order motions at the deck. These first order deck motions are comparable to those of other FPS concepts. First order motions at the keel (i.e., 600-700 feet below the surface) are almost non-existence. Second order wave forces cause resonant surge and pitch responses. The center of pitch for these resonant motions is close to the center of mass, which for deep draft SPAR is usually 10-20 feet below the centroid of displacement (i.e., around 335-345 feet below the water surface for a 650 feet draft). Model tests and analyses suggest that first and second order responses at the C.G. in a Gulf of Mexico type hurricane environment are approximately equal in surge and pitch.

The amplitude of the low frequency motions depends on the stiffness of the mooring system and the system damping. It is to be noted that the low frequency motion, in most systems with tanker type vessels, is a dominating design load for the mooring system. The method of calculating stiffness of the mooring system is not difficult; but there is a substantial degree of uncertainty in estimating the hydrodynamic characteristics such as damping and added mass for large tankers and other vessels.

Since the SPAR structure with a large well bay within the hull is a novel structure, it is recommended that the wave induced motion of such structure should be determined by model tests in a wave basin. The hydrodynamic characteristics of such a structure, such as, damping, added mass, etc. calculated by most of the readily available hydrodynamics software may not be reliable unless calibrated with model tests.

Vortex Shedding

It is found in various model test that a SPAR based FPS is susceptible to vortex induced vibrations (VIV). Spiral strakes when fitted to the SPAR hull tend to minimize the vortex shedding. The size and orientation of strakes is to be selected by model test. Though, it is generally believed that a cylindrical hull with spiral strakes may have a tendency of spinning during tow, one recent model test for towing did not show any spinning. Nevertheless, it is recommended that suppression capability and towing feasibility be verified by testing hull fitted with strakes in a wave basin.

Design Environmental Conditions

In the design of a SPAR based floating production system, it is required to identify relevant design conditions as appropriate to different modes of operation of the system. For example. the mooring system of a SPAR based floating platform is to be designed to survive the Design Extreme Condition and to operate in the Maximum Operating Condition.

Design Extreme Condition

This is defined as an extreme condition with a specific combination of wind, waves and current for which the mooring system is to be designed. It is also called the Maximum Design Condition. The extreme condition recurs quite rarely during the service life of the floating production system at a particular site.

A minimum return period of 100 years for the design extreme condition should be used for FPS's of any kind with service life greater than 2-1/2 years unless convincing evidence and analysis (such as risk analysis) assures that any damage at survival condition will not be catastrophic by nature.

The Design Extreme Condition in the Gulf of Mexico with respect to the mooring system could be due to either an extreme hurricane event or an extreme loop current event. The Design Extreme Environment is to be the one of the following:

100-year waves with associated wind and current;

100-year wind with associated waves and current; and

100-year loop current with associate wave and wind.

For FPSs with service life less than or equal to 2-1/2 years, the minimum return period of 50 years with wind speed not less than 50 knots may be considered for the design.

Design Operating Condition

It is defined as the limiting environmental condition at which normal operations would require to be suspended. This condition might be expected to occur one or more times in a year without damaging any component of the system.

Design Installation Condition

This is generally dependent on the time of the year the installation is envisioned at a particular site. Various design and analyses, e.g., stability of the hull, structural adequacy under any static hydrostatic pressure, for any condition expected during the installation are to be performed. For the design and analyses for installation engineering, the designer is to use the limiting environmental data for installation. These data are to be established with the considerations of duration of installation, quality of weather forecasting, and contingency plan.

Transportation Condition

It is believed that the SPAR hull can be built inexpensively in a shipyard or fabrication yard in South East Asia, Europe or in U.S.A. The fabricated hull can then be either "wet" towed or "dry" towed to the installation site. It is interesting to note that the longitudinal strength of the SPAR hull may be governed by the wet tow condition even though that environmental condition is much milder than the design extreme condition. The design should verify the adequacy of stability and structural strength during tow. The designer will have to determine the towing resistance of the hull, and the tug power requirement.

For a dry tow on a transporting vessel, the stability of the transporting vessel and sea fastening design of various items onboard may be critical during transportation. Since the sea fastening designs are governed by the wave induced motions, the design environmental conditions which would create the design sea fastening forces should be established. The design sea state however depends on the route, time of the year, weather forecasting capability, contingency plans, etc.

System Conditions

The various conditions of a floating production system which are important for the designer to consider are as follows:

Intact Operating

A condition with all components of the system intact and exposed to an environment as described by the design operating condition.

Intact Extreme

A condition with all components of the system intact and exposed to an environment as described by the design extreme condition.

Broken Line Extreme

A condition with any one mooring line broken at the design extreme condition which would cause maximum mooring line load for the system. It should be noted that the mooring line with the maximum load in intact extreme condition when broken may not cause the highest mooring line load for the system with remaining intact lines.

Damage Compartmentation

A condition with one compartment damaged for evaluating damage stability of the unit. The extent of damage is in accordance with ABS Rules for Building and Classing Mobile Offshore Drilling Units (1991) section 5 and 6. A reduced wind speed of 50 knots is used for evaluating the damage stability of the unit.

STATION KEEPING SYSTEMS

The mooring, anchoring, and dynamic positioning (if there is any) system are part of the station keeping system. The objective of the station keeping system is to keep the floating production system on station at a specific site.

Mooring System

For a SPAR based FPS, generally the conventional spread mooring system with drag or pile anchors is considered for station keeping purposes. Alternatively, a taut mooring system with pile anchors has also been reported to be feasible for this application.

Mooring Analysis

The analysis of a mooring system for a floating production system includes the determination of the extreme response of the vessel in the design environmental condition and the corresponding mooring line tension. A moored system is a dynamic system which is subjected to steady forces of wind, current and mean drift force as well as the wave induced dynamic response of the vessel.

The calculations of steady forces due to wind and current are outlined earlier and the available methods of calculating hydrodynamic characteristics and hydrodynamic loading are also indicated. The drift forces on a moored vessel consist of a mean wave drift force along with the slowly varying oscillatory drift force at or near the natural period of the spring-mass system of the moored vessel. The mean and oscillatory low frequency drift forces may be determined by model tests or by using hydrodynamic computer programs calibrated against model test results or other data.

Maximum Offset of the Vessel

The wave induced vessel dynamic responses can be calculated by either frequency domain or time domain. The maximum offset consists of offset due to wind, current and wave (steady drift), wave frequency motions and low frequency motions and are to be determined as follows in accordance with API RP 2FP1:

$$S_{max} = S_{mean} + S_{lf(max)} + S_{wf(sig)} \quad \text{or}$$

$$S_{max} = S_{mean} + S_{lf(sig)} + S_{wf(max)} \quad \text{whichever is greater.}$$

where:

S_{mean} = Mean vessel offset due to wind, current and mean (steady) drift force.

$S_{lf(sig)}$ = Significant single amplitude low frequency motion.

$S_{wf(sig)}$ = Significant single amplitude wave frequency motion.

Alternately the maximum excursion can be determined either by time domain simulation or by model test.

The maximum values of low frequency motion $S_{lf(max)}$ and wave frequency motion $S_{wf(max)}$ may be calculated by multiplying the corresponding significant single amplitude values by a factor

$$C = \sqrt{(2 \times \ln N)} ;$$

where

$N = T/T_a$; for specified storm duration T(seconds), and average zero up-crossing period T_a(seconds). For low frequency components, T_a can be taken as the natural period T_n of the vessel. T_n can be estimated from the vessel mass "m" (including added mass in slugs) and mooring system stiffness "k" in lbs/ft taken at the vessel's mean position as follows:

$$T_n = 2 \pi \times \sqrt{(m/k)}$$

Maximum Line Tension

The mean tension in a mooring line corresponds to the mean offset of the vessel. The design (maximum) mooring line tension T_{max} may be determined as outlined in API RP 2FP1 which is summarized below:

$$T_{max} = T_{mean} + T_{lf(max)} + T_{wf(sig)}; \text{ or}$$

$$T_{max} = T_{mean} + T_{lf(sig)} + T_{wf(max)}; \quad \text{whichever is greater.}$$

where:

T_{mean} = Mean mooring line tension due to wind, current and mean (steady) drift force.

$T_{lf(sig)}$ = Significant single amplitude low frequency tension.

$T_{wf(sig)}$ = Significant single amplitude wave frequency tension.

The maximum values of low frequency tension $T_{lf(max)}$ and wave frequency tension $T_{wf(max)}$ are to be calculated in the same procedure as that of obtaining the motions at wave frequency and low frequency.

Mooring Line Fatigue Analysis

The fatigue life of mooring lines should be assessed using T-N approach using an appropriate T-N curve which gives the number of cycles "N" to failure for a specific tension range "T". The fatigue damage ratio, D_i for a particular sea state "i" is estimated in accordance with the Miner's Rule as follows:

$$D_i = (n_i / N_i);$$

where:

n_i = number of cycles within the tension range interval "i" for a given sea state.

N_i = number of cycles to failure at tension range i as given by the appropriate T-N curve.

The cumulative fatigue damage "D" for all the expected number of sea states "NN" (identified in wave scatter diagram) should be calculated as:

$$D = \sum_{i=1}^{NN} D_i$$

D should not exceed unity for the design life which is the field service life multiplied by a factor of safety as quoted in Table 4.

It is recommended to perform a detailed fatigue analysis following the procedure outlined in section 6.3 of API RP2FP1.

Mooring Line Design

The mooring lines should be designed with the factors of safety quoted in Table 4 with respect to the breaking strength and fatigue characteristics of mooring lines. These factors of safety are dependent on the design conditions of the system as well as the level of analyses.

Table 4

Factor of Safety for Anchoring Lines

		Factor of Safety
Anchor Chains:		
Mooring Component Fatigue Life w.r.t Design Service Life		3.00
Dynamic Analysis		
All line intact	Dynamic Analysis	1.67
One broken Line		1.33

Anchor Holding Power

Two types of anchor, i.e., Drag Anchor and Pile Anchor are the most probable applications for floating production system.

Drag Anchor

Traditionally drag anchors are designed such that they are not subjected to any uplift force. Accordingly, the mooring line length should be sufficient for the lines to remain tangent to the sea bed when the mooring line is subjected to the maximum design load at intact extreme condition or at broken line extreme condition, whichever is greater.

Recent studies indicate that the high holding capacity anchors are capable of resisting a substantial vertical loading for soft clay conditions similar to that of the Gulf of Mexico. Accordingly, the draft version of API RP on "Design and Analysis of Stationkeeping systems for Floating Structures" reports that anchors subjected to loading at angle up to 30° do not lose their holding capacity. Since this is a major deviation from the general practice of mooring line angle of 0° at the sea bed, ABS is prepared to accept of mooring line angles of 5° and 10° for the intact and broken line cases respectively on a case by case basis for the soft clay condition. At the same time, for the sake of conservatism ABS requires a higher factor of safety of 1.25 for the anchor for the broken line case as quoted in Table 5.

A drag anchor's holding power depends on the anchor type as well as the condition of the anchor deployed in regard to penetration of the flukes, opening of the flukes, depth of burial, stability of the anchor during dragging, soil characteristics, etc. The designer should submit to the Bureau the performance data for the specific anchor type and soil condition, if available. Because of uncertainties and wide variation of anchor characteristics, adequacy of holding power is to be verified by pull test after the anchor is deployed.

The maximum load at anchor F_{anchor} is to be calculated as follows:

$$F_{anchor} = P_{line} - W_{sub} \times WD - F_{fr};$$

$$F_{fr} = f \times L_{bed} \times W_{sub}$$

where:

P_{line} = maximum mooring line tension

WD = Water Depth

f = coefficient of friction between mooring line on sea bed and the sea bed

L_{bed} = length of mooring line on sea bed

W_{sub} = submerged unit weight of mooring line

The coefficient of friction *"f"* depends on the soil condition and the type of mooring line. For soft mud, sand and clay the following values (from API RP 2FP1) of *"f"* for wire rope and chain may be considered as representative:

	Coefficient of Friction *"f"*	
	Starting	Sliding
Chain	1.00	0.70
Wire Rope	0.60	0.25

Pile Anchor

Pile anchors are capable of withstanding uplift and lateral forces at the same time. Analysis of pile as a beam column on an elastic foundation should be submitted to the Bureau for review. The analyses for different kinds of soil are outlined in section 6 of API RP 2A.

Factor of Safety

The factors of safety in the design of anchors are summarized below in Table 5.

Table 5

Factors of Safety of Anchors

	Factor of Safety
Drag Anchors	
Intact Extreme	1.50
Broken Line Extreme	1.00
for anchor subjected to uplift	*1.25*
Pile Anchors	
(Please refer to API RP 2A)	

Field Test

After the mooring system is deployed, each mooring line will be required to be pull tested. During the test each mooring line will be pulled to the maximum design load for intact extreme condition and held at that load for 30 minutes.

Mooring Equipment

Mooring equipment for floating production systems includes winches, windlasses, chain, wire rope, in line buoys and fairleads. In selecting mooring equipment for a specific application, care is to be taken to ensure the equipment is suitable for the loading for which the system is required to maintain position, as determined by the mooring analysis. Appropriate factors of safety are to be incorporated into the design of all mooring equipment.

Mooring equipment is to comply with the applicable ABS published requirements, in instances where ABS published requirements do not exist, the equipment is to comply with an applicable recognized industry standard. Applicable ABS requirements and industry standards for mooring equipment are indicated by check marks ("√") in the following table.

	Buoyancy Tanks	*Chain*	*Winches & Windlasses*	*Wire Rope*
ABS ***Guide for Offshore Mooring Chain***	-	√	-	-
ABS ***MODU Rules*** Section 3/12	-		√	-
API Spec 9A & RP 9B	-	-	-	√
ASME Boiler and Pressure Vessel Code	√	-	-	-

For the design of fairleads, the primary consideration is that the wire rope is to fail before the fairlead. In general the design load for the fairlead and its connection to the vessel would be the breaking strength for the wire ropes or platform chain and the allowable stress for the material would be 80% of its yield point. This approach ensures a factor of safety of 25% with respect to the breaking strength of the wire rope.

STRUCTURAL STRENGTH AND ARRANGEMENT

The SPAR structure is to be adequately designed for all the various loading conditions that it may have to undergo during its entire service life. Though most of the time the SPAR will be in upright condition supporting the production equipment, the SPAR hull will be going through various orientations, i.e., from horizontal during tow on to intermediate conditions during upending. The hull structure can be designed either as ring stiffened or longitudinally framed with intermediate ring stiffened structure. In general the structural arrangement of the hull will be orthogonally stiffened plates which is similar to that of any ship or Mobile Offshore Drilling Unit (MODU).

Loadings on the SPAR Unit

Applied Loadings are to include the effects of gravity loads, environmental loads, and equipment loads on the structure.

The loads produced by items such as production facilities equipment related to drilling, risers and riser tensioners, and mooring line loads on fairleads and winches are also to be given special consideration.

Longitudinal Strength

For a wet tow of the hull, the structure will be subjected to wave induced hogging and sagging moments. Thus the structural arrangement should have longitudinal framing to provide adequate longitudinal strength to withstand the wave induced bending moments during the tow along the length of the SPAR. The longitudinal strength of the hull is provided by the shell plating, and the longitudinal structural members, such as the deep girders, stiffeners, etc. The strength of the structure during upending should also be checked appropriately.

Structural Scantlings and Details

The designer may refer to ABS ***Steel Vessel (SV) Rules*** and/or *MODU Rules* for designing the scantling of the SPAR hull. API Bul 2U and 2V may also be referred to. The scantlings are usually designed with structural angles, channels, bars, and rolled or built-up sections. The section modulii of members such as girders, webs, etc., supporting frames and stiffeners are to be calculated incorporating an effective width of plating.

The designer should give special consideration in developing the design details in regard to the following:

- thicknesses of members in locations susceptible to corrosion
- proportions of built-up members to comply with established standards for buckling strength
- minimizing stress concentrations and notches

- proportionality and thickness of structural members for better fatigue characteristics

Local Structures

The structures in way of the concentrated loads from the module skids, derrick, equipment, etc. are to be reinforced adequately. The structures in way of the mooring system are to be capable of withstanding forces (obtained as the maximum of all the design conditions considered) from the system and are to be reinforced appropriately.

Fatigue

The fatigue damage due to cyclic loading is to be considered in the design of the structure. A ***fatigue analysis*** using an appropriate loading spectrum in accordance with accepted theories and "*Miner's Rule*" for calculating "accumulated damage" is acceptable.

The designer may refer to the following references:

Reference	*Section*
API RP2A	5.2
UK HSE Guidance Notes	21.2.10-21.2.15, A21.2.12a, A21.2.13

Other accepted methods (such as fracture mechanics) of calculating fatigue life may also be considered for certain elements.

The minimum allowable fatigue life is to be "FS" times the design service life; where "FS" is the factor of safety. "FS" depends on the inspectability of the structure as well as the criticality of the structure. The "FS" values to be used in calculating the minimum fatigue life are as follows:

FS = 3.00 for areas which are easy to inspect and are "non-critical" areas

= 10.00 for areas which are non-inspectable or "critical" areas. The word "critical" implies that failure of these structural items would result in progressive failure of the structure and may lead to a catastrophe.

Stability

The stability of the SPAR is to be evaluated so as to ensure it is stable in any loading condition. Since there are no specific rules for evaluating stability for such a platform, the requirements for MODUs can be applied with proper judgments.

The platform is to have positive metacentric height in calm water equilibrium position, for all afloat conditions, including temporary positions during fabrication, installation, ballasting, deballasting, and other marine operations. The stability should be evaluated during any wet tow, during the upending sequences, and for the in place condition.

The platform should have sufficient stability in the intact as well as the damaged condition. The intact and the damage stability to withstand the overturning effect of the force produced by the defined "operating intact wind", "severe storm intact wind", and "damaged wind" should be investigated in accordance with 3/3.3.2 of the ***ABS MODU Rules***. The wind velocities for calculating the wind overturning moments are to be established using the site specific environmental report and are to be identified in the design basis. The wind velocities which are used in the classifications of MODUs for unrestricted service are quoted below for reference.

Conditions	*Minimum Wind Velocity*	
Damaged	*25.8 m/s*	*(50 kts)*
Operating Intact	*36.0 m/s*	*(70 kts)*
Severe Storm Intact	*51.5 m/s*	*(100kts)*

It is prudent not to use wind velocity less than 50 knots for evaluating stability of the vessel at any critical loading conditions. The stability analysis is to be carried out with the assumption that the unit is floating free of mooring restraints. The detrimental effects of catenary mooring systems, if any, should be considered appropriately.

During any ballast or deballast operation, the platform must comply with the above positive metacentric height requirement, and the free surface corrections are to properly accounted for.

Operating Manual

An operating manual should contain a summary of Loading, Environmental and Stability Criteria. It is to include the environmental conditions and associated limitations, if any, on the unit and the loadings for which the structure is designed. The summary is to include the maximum vertical center of gravity (VCG) above the keel versus draft curves or Tables. It should clearly define the loading conditions in regard to draft, ballast load, free surface corrections, etc.

For a floating production system in the Outer Continental Shelf (OCS), the designer may refer to 46 CFR Ch. I, section 109.121 for the items to be addressed as required by the United States Coast Guard.

Regulatory Requirements

The various regulations which are applicable to the Outer Continental Shelf (OCS) of the United States are primarily set by the Minerals Management Service (MMS) and the United States Coast Guard (USCG).

A site specific floating production system (FPS) falls under the jurisdiction of the MMS which requires an operating permit and compliance with the MMS requirements as outlined in the Code of Federal Regulations (CFR) 30 CFR 250 subpart I. Although this part of the CFR does not mention FPS specifically, MMS's intention is to treat such system on a case by case basis. Since USCG is very much concerned with the marine safety, they also have important role in inspection and review of such facilities.

In general, MMS is concerned with production and industrial process system safety and with environmental impact. The MMS's responsibilities are primarily related to the management of mineral leasing on the OCS and regulating all mineral exploration, drilling, completion, workover, and production activities on leased or leasable land.
USCG on the other hand is more concerned with the "ship's service" type marine engineering, electrical systems. The USCG's regulatory responsibility also includes promoting safety of life and property on OCS facilities and on vessels engaged in OCS activities.

For production facilities on the OCS, MMS and USCG came to an agreement through a Memorandum of Understanding (MOU) about their responsibilities in promoting safety of personnel, activities, and facilities associated with exploration, development, production, and processing of mineral resources. Based on this MOU, the responsibilities of MMS and USCG can be summarized as presented in Table 6.

Reference Materials for Designing SPAR based Platforms

The following materials provide useful guidance to the designer:

- ABS Rules for Building and Classing of

  Steel Vessels

  Mobile Offshore Drilling Units

- ABS Guide for Building and Classing Floating Production Storage Systems, February 1994.

- API Recommended Practices

  RP 2FP1 (Draft), Design, Analysis, and Maintenance of Moorings for Floating Production System", 1st Edition, February 1, 1993.

  RP 2A-WSD, Planning, Designing and Constructing Fixed Offshore Platforms Working Stress Design, 20th Ed., July 1, 1993.

  RP 2A-LRFD, Planning, Designing and Constructing Fixed Offshore Platforms Load and Resistance Factor Design, 1st Ed., July 1, 1993.

  RP 2T, Planning, Designing and Constructing Tension Leg Platforms, First Edition, April 1987.

  API Bulletins

  Bull 2U, Bulletin on Stability Design of Cylindrical Shells, 1st Ed., May 1987 (ANSI/API Bull 2U-1992).

  Bull 2V, Bulletin on Design of Flat Plate Structures, 1st Ed., May 1987 (ANSI/API Bull 2V-1992).

- AISC Manual of Steel Construction - Allowable Stress Design.

- American Welding Society (AWS) - Structural Welding Code - Steel Member (D1.1).

Table 6

Rsponsibilities of MMS and USCG Related to Overseeing OCS Facility Design and Construction, Systems and Equipment, and Operations

ITEMS	MMS	USCG
Facility Design & Construction	a. Site Specific: Oceanographic, Geotechnical, meteorological, geophysical, etc. b. Mooring and Anchor System. c. Structural design, fabrication, and installation. Modification and repair works. d. General Arrangement of Production, Well control, Safety System and Equipment.	USCG will be concerned with all OCS drilling facilities & facility such as a SPAR based FPS which will require USCG COI: a. Structural design, fabrication, installation. Modification and repair works. b. General Arrangement, Stability and Buoyancy in transit and operational mode. c. Structural fire protection, evacuation plan, escape routes, ventilation systems. d. Workplace safety, and Lifesaving equipment.
Systems and Equipment	a. Blowout preventer and other well control equipment, wellhead, flowline, pipeline, well test equipment including safety valves and pressure sensors, dehydration equipment and gas compressor units, H_2S control equipment, gas detection systems, and personnel protection. Gas detection systems for production or associated equipment. b. Production safety systems. Production associated piping systems, pumps to transfer liquids within the production systems & into pipelines. Pressure, atmospheric, and fired vessels and piping used for production operations.	a. Establish systems and equipment requirements, as appropriate for alarm, lifesaving equipment. b. Fire detection, control and extinguishing systems and equipment. c. Living quarters, navigation lights, communications, obstruction lights, and sound signals. d. Mooring components - rating, and facility compatibility; and not the site specific requirements.

(Continued)

Table 6

Rsponsibilities of MMS and USCG Related to Overseeing OCS Facility ***(continued)***

ITEMS	MMS	USCG
Systems and Equipment (cont'd)	c. Emergency Shut Down (ESD) system to initiate facility shutdown, activated manually or by gas sensors, fire detectors (heat, smoke, or flame), or fire loop in wellhead, production, and living quarter areas. d. Subsea completions. Containment systems for overflow from equipment associated with drilling and production.	e. Helideck installations including helicopter refueling facilities, cranes, booms and material handling equipment. **NOTE:** *USCG will not, however, establish requirements for production or workover equipment that would conflict with MMS requirements.*
Operations in regard to administration of procedures in regard to training, drills, inspection and emergency.	a. Production operations including well control & control of H_2 S. b. Pollution prevention, helicopter operations and fire fighting. c. Safe welding, burning on non structural members, structural inspections and repair. d. Pipeline operations, well-head and platform removal. e. Transfer of material and personnel on or off the vessel.	a. Emergency egress and use of lifesaving/emergency equipment. b. Handling, transfer, and stowage of explosives, radioactive, flammable, and other hazardous material. c. Transfer of Petroleum and other products from or to a vessel. d. Vessel operations as well as diving operations. e. Pollution response and compensation, occupational safety, and health of personnel.
Inspections	a. Annual, scheduled, and unannounced inspections. Report deficiencies which may fall within the responsibility of the other Agency for action. b. Administers shutdown of production operations and may initiate such shutdown upon request by USCG.	a. Annual, scheduled, and unannounced inspections. Report deficiencies which may fall within the responsibility of the other Agency for action. b. Issue of Certificate of Inspection (COI).

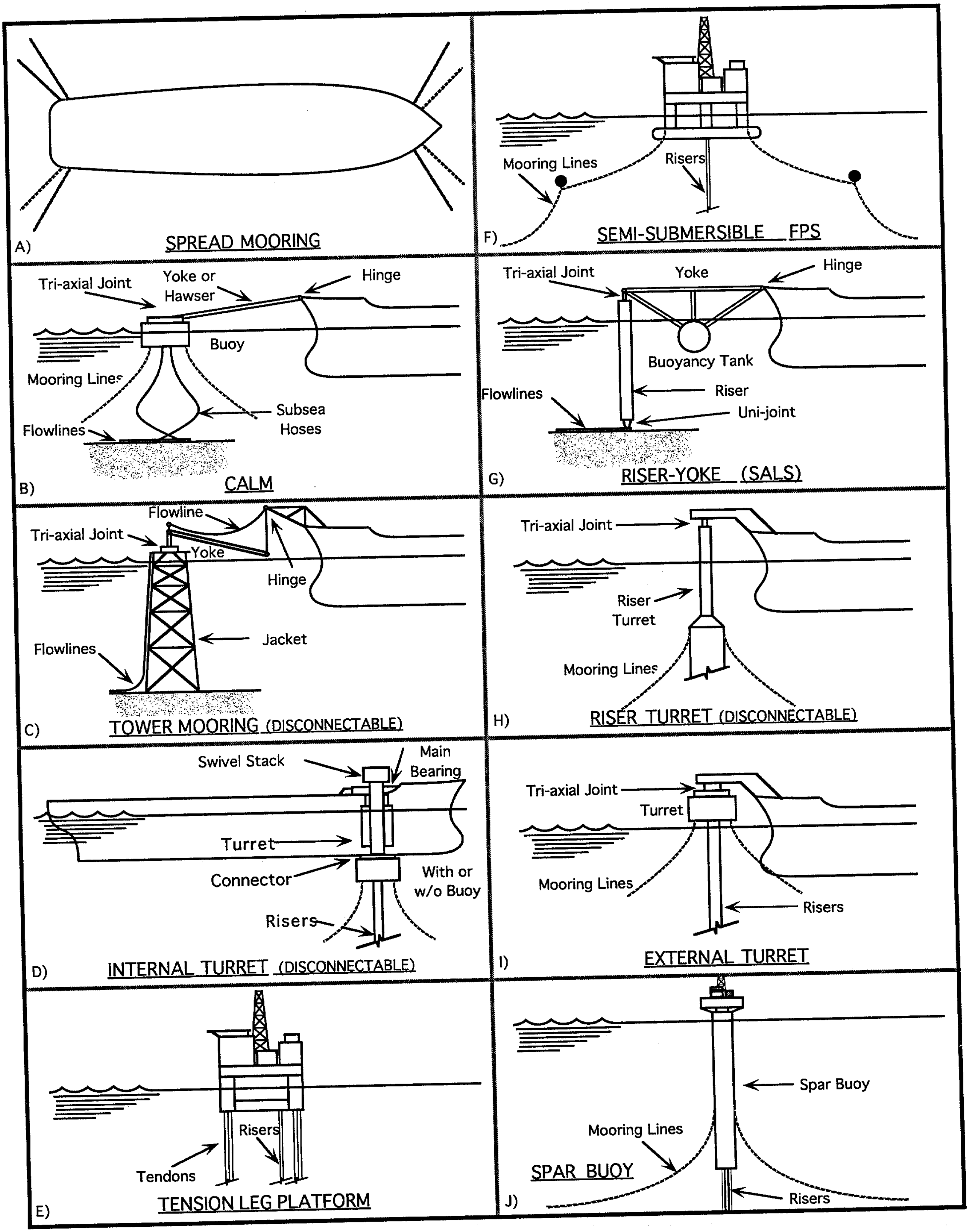


Figure 1 Types of Mooring Systems

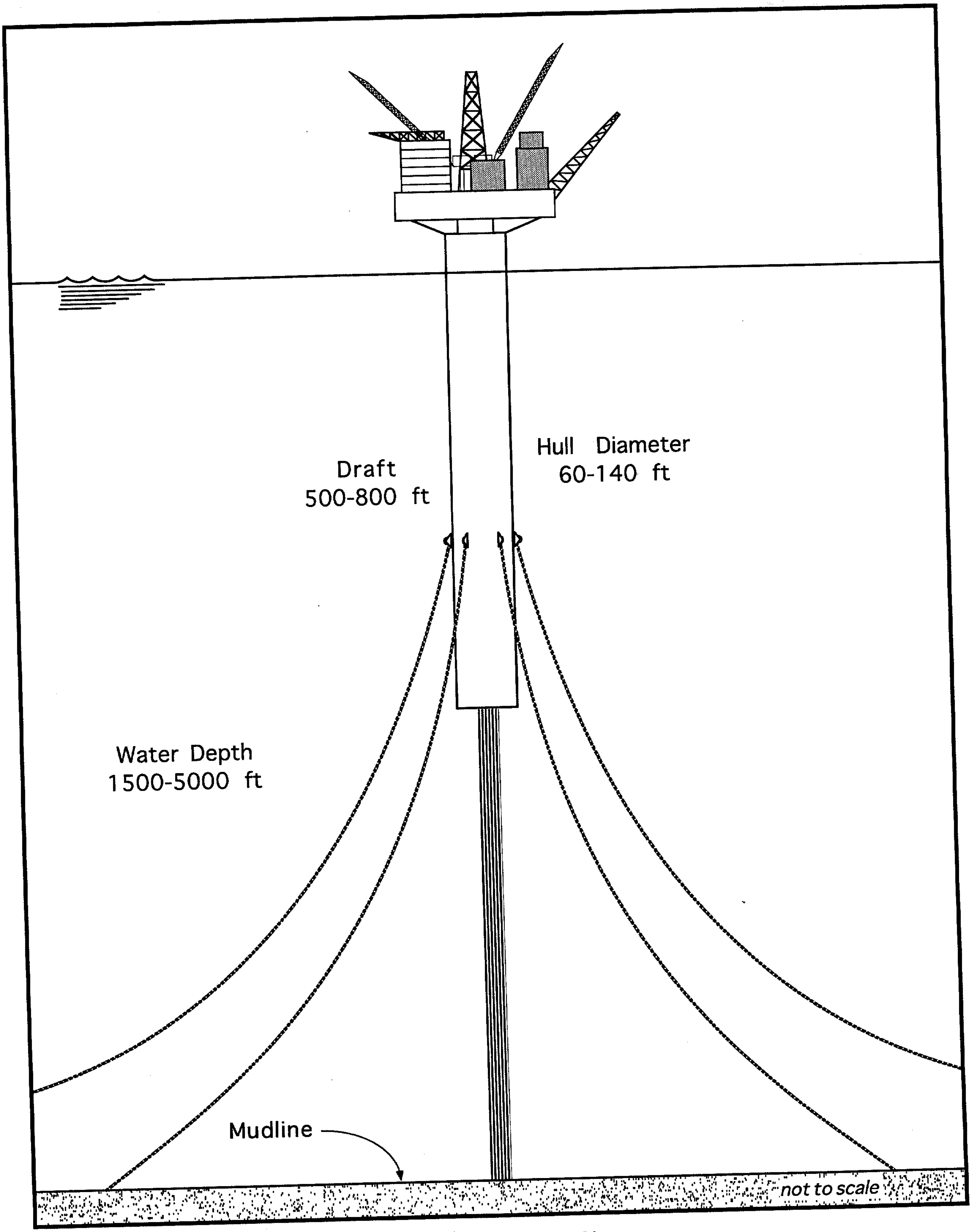
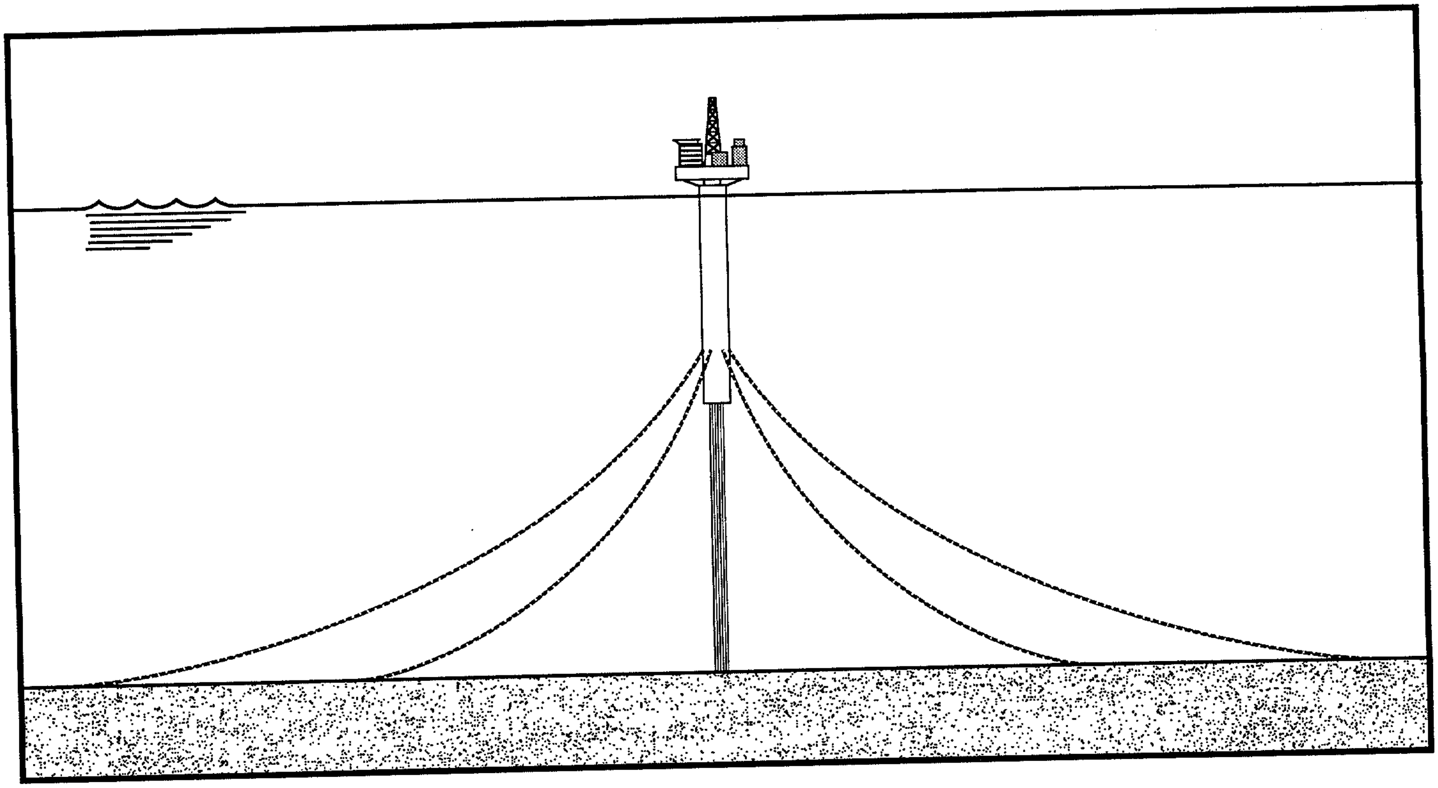
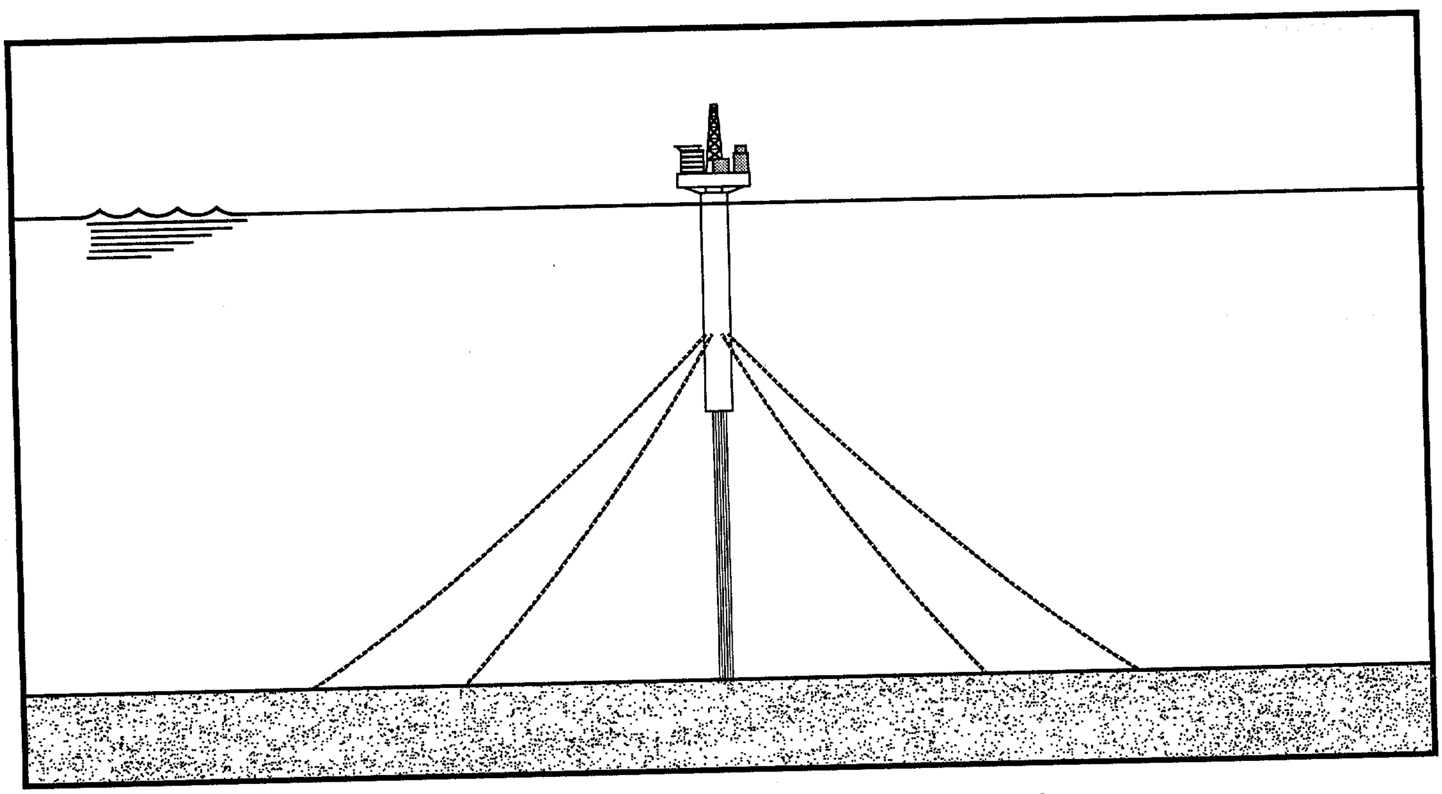


Figure 2 Profile



a) Catenary Spread Mooring Arrangement



b) Taut Spread Mooring Arrangement

Figure 3 SPAR Buoy Mooring Arrangements

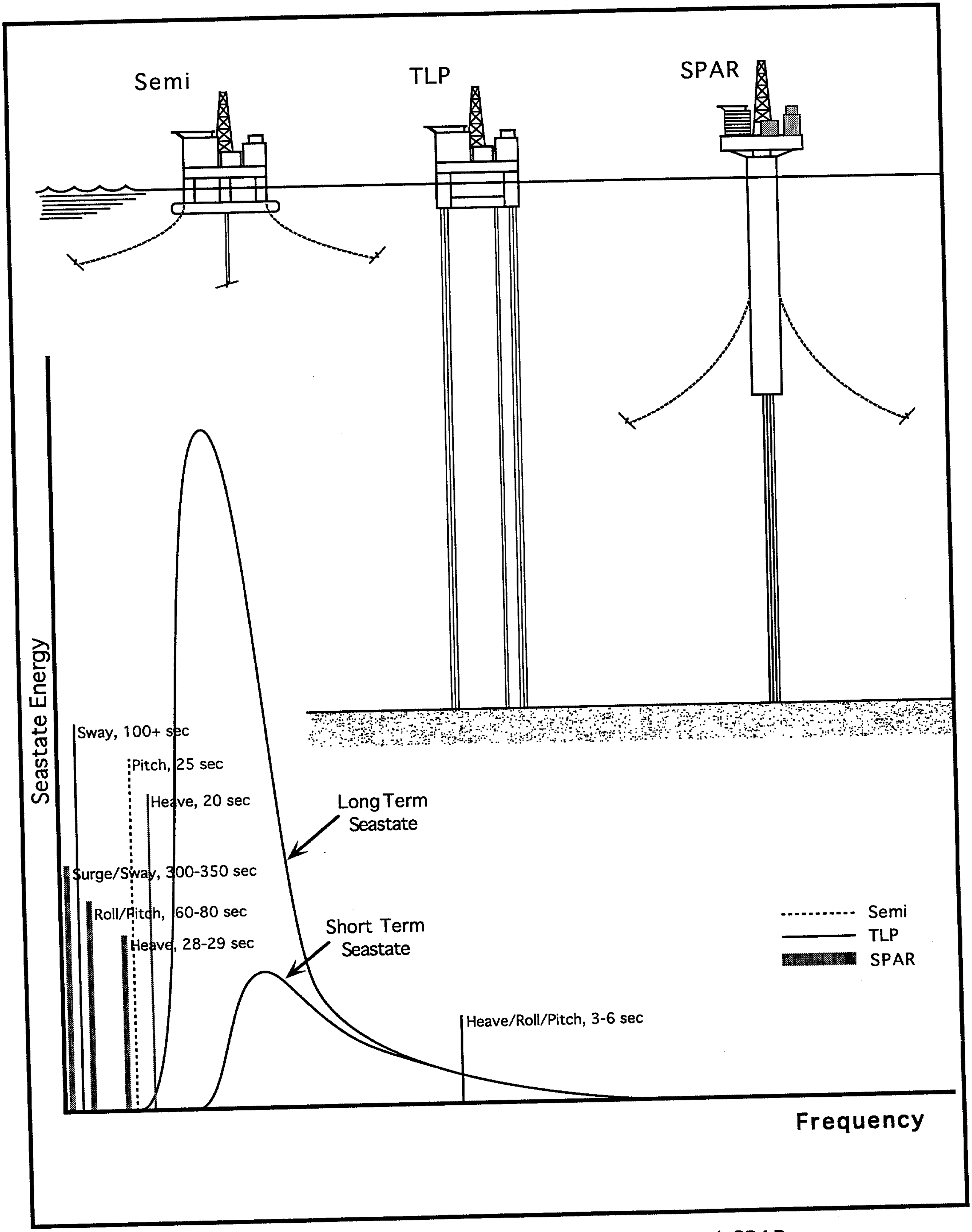


Figure 4 Natural Periods of TLP, Semi, and SPAR