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Turret Moorings for Extreme Design Conditions

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ABSTRACT

Floating production storage and offloading systems are being designed and constructed for conditions that redefine current thinking regarding the "state-of-the-art". This paper describes four such projects currently underway (by SOFEC) that illustrate some of these extremes, i.e., violent environmental conditions both cyclonic and sustained, very deep and very shallow water depths, large numbers of risers, and high operating pressures. These projects clearly demonstrate the versatility of turret moorings and FPSO's and the descriptions herein of these actual projects will provide a useful tool for comparative analysis of potential future projects.

INTRODUCTION

The first turret moorings in the offshore industry were used on "Discoverer" Class drillships developed in the 1960's by The Offshore Company. This background of experience combined with Single Point Mooring (SPM) technology has led to the development of today's sophisticated and elegant turret mooring systems.[1]

The growing demand coupled with proven performance of Floating Production Storage and Offloading Systems has resulted in an ever increasing design envelope. The FPSO concept once thought primarily applicable to the development of marginal fields, has in fact proven itself a viable option for major oil fields located in areas that lack significant infrastructure.

When compared to semi-submersible based developments in such areas, the FPSO, which provides both storage and offloading capabilities in one facility, will nearly always prove to be the more attractive development option.[2]

INTERNAL TURRET SYSTEMS

Quickly becoming one of the most common moorings for extreme design conditions is the internal turret mooring system. Available as either a permanent or a disconnectable system, the internal turret mooring is

References and figures at end of paper.

recognized for its versatility in moderate to deep water depths, for locations having violent environmental conditions, and for applications requiring large numbers of flexible risers. Following are two interesting examples of internal turret systems currently being designed for extreme conditions.

Project: **Amoco Orient Petroleum Company**
Location: **"Liuhua 11-1" Field**
People's Republic of China
Water Depth: **293 meters (960 feet)**

The Liuhua 11-1 field is a subsea development having 20 clustered satellite wells and floating facilities which include both a semi-submersible and an FPSO. The semi-submersible supports the control umbilicals for the downhole pumping operations and the FPSO, which is the 141,000 DWT converted Amoco tanker "Mega Eagle", provides final processing, water removal, crude stabilization, storage, metering, and offloading (FIGURE 1).

It was decided early in the project to utilize a permanent turret mooring (FIGURE 2) as opposed to the disconnectable type turrets used on two previous "typhoon alley" projects. This meant the FPSO had to remain moored during the 100-year typhoon characterized by significant wave heights up to 15 meters, currents in excess of 3 knots, and 87 knot winds. Design forces and motions developed during extensive model tests conducted at the Norwegian Marine Technology Research Institute (MARINTEK) correlated well with those developed analytically during preliminary design.

A separate series of wave basin tests was also conducted to determine the effects of "greenwater" over the forecastle deck when the tanker was in a loaded condition. As a result of these tests which showed greenwater as high as 3 meters above the main deck at the turret location, it was decided to erect a greenwater deflection shield forward of the turret. The greenwater tests were conducted at Maritime Research Institute Netherlands (MARIN).

Another challenging design condition was the regular occurrence of soliton currents which are common to the "typhoon alley" area offshore China. Solitons are tidal induced internal waves which travel along isotherms well below the sea surface at velocities up to 6 knots. The effects of the soliton currents were studied analytically and did not significantly impact the mooring line forces, while the "inverted catenary" mooring design prevented contact between the risers and the anchor legs (FIGURE 3).

The turret system design philosophy considered simplified fabrication, ease of maintenance, high safety and reliability together with low technical risk. Design features include:

- The turret is a 360 degree free weathervaning design which does not require a power drive mechanism for rotation.
- The turret includes a fluid swivel assembly rather than a bulky drag chain system. Drag chain systems restrict free weathervaning capability to approximately 270 degrees and typically require a thruster system for driving the tanker around the mooring.
- The main bearing is located at the top deck where it is readily accessible for inspection and preventative maintenance.
- In-situ machining operations are not required to mount the bearing.
- Internal chain hawses eliminate the requirement for turret rotation during installation (and retensioning) which substantially reduces installation costs.

The turret design is configured around a 6.5 meter diameter shaft supported by a three-row roller bearing at the FPSO's top deck. The lower turret module connects with the anchor chain table which is recessed above the vessel's keel. The anchor chain table supports ten ratcheting type chain stoppers mounted on trunnions fitted with permanently lubricated bushings to allow free alignment of the mooring legs.

The main bearing, manufactured by RKS, is equipped with U.T. monitoring and automatic lubrication systems and is designed to support the total vertical load of the moorings and risers. The bearing is completely enclosed in a fully sealed steel housing which protects it from saltwater and other contaminants. The bearing is mounted to the vessel through a stiffened circular ring which distributes loads to the horizontal support assemblies and the equally spaced flexible elements that provide vertical support. This unique "flexible" foundation reduces turret shaft fixity and thus limits bearing roller loads which would result from flexure of the turret shaft.

The FPSO receives raw crude oil from the semi-submersible via two 12 inch flexible flowlines and risers plus one 6 inch well test line. These flexible lines are routed through hard pipe riser guide tubes inside the turret shaft to the manifold center located above the FPSO's main deck. The 60 ton fluid swivel assembly incorporates two 12 inch toroidal swivels, one 6 inch in-line swivel, and a hydraulic control swivel (FIGURE 4). The fluid transfer system is designed for 300,000 barrels per day at maximum flow velocities of 15 feet per second.

The FPSO will be moored with a symmetrical, ten leg composite wire/chain system and high capacity drag embedment anchors. The mooring legs each incorporate a single intermediate support buoy which forms an "inverted catenary" configuration. This type of design, unique for a weathervaning monohull provides several important advantages when compared to conventional catenary mooring systems :

- The inverted catenary design has a linear force-deflection characteristic which minimizes large force increases at small displacement offsets.
- Total vertical loads are reduced which simplifies turret design and reduces mooring system cost.
- The intermediate support buoys increase the torsional restraint of the mooring so that a turret drive system is not required.
- Wave frequency mooring line loads are reduced which minimizes system fatigue.
- The mooring configuration provides a very wide "window" for flexible risers thus eliminating contact between the mooring legs and the risers in any condition.
- The support buoys simplify the installation procedure and significantly reduce installation costs.

Project: **Petrobras**
Location: **"Barracuda" Field Brazil**
Water Depth: **835 meters (2739 feet)**

The Barracuda field is an 11 well subsea development which will utilize a deepwater FPSO moored with a permanent internal turret. When installed, this system will become the world's deepest FPSO system, far surpassing the design water depth of other similar systems. In addition, because of the field layout which includes individual satellite wells, a total of 34 flexible risers will be required to produce the field. This constitutes the largest number of flexible risers ever accommodated by a tanker based FPSO and the largest number of flowpaths ever to be manifolded in an internal turret system.

The environment offshore Brazil has wind and waves predominately from the South with significant wave heights of 7.2 meters, wind velocities up to 68 knots, and currents of 2.7 knots. When the weather is from the North, strong currents up to about 4 knots can occur (FIGURE 5).

Like the previously described project, the turret design is based upon a turret shaft supported by a three-row roller bearing located at the FPSO's top deck (FIGURE 6). The large number of risers dictates a much larger diameter turret shaft and the loads imposed by these risers control the design requirements for the main bearing. The load combinations that result from the large number of risers and anchor leg loads do not dictate use of a lower bearing to control flexural loads on the main bearing.

Additionally, the large size of turret shaft permits the chain support assemblies to mount internally thus eliminating a below keel chain table. This allows the turret to be mounted without extended drydocking of the FPSO vessel.

The 34 risers are suspended below the turret and hang in a natural catenary configuration all the way to the seafloor (FIGURE 7). Inside the turret, the risers are routed through riser guide tubes arranged around the periphery of the turret shaft i.d. in a manner that avoids undue congestion in the turret area during installation and operation (FIGURE 6). The risers terminate in a complex well control manifold located upstream of the fluid swivel. The required risers and umbilicals are as follows:

Production Risers:	11 x 4 inch i.d. @ 3000 psi
Gas Lift:	11 x 2.5 inch i.d. @ 3000 psi
Control Umbilical:	11 x 4.5 inch o.d.
Gas Export:	1 x 11 inch i.d. @ 2000 psi

The fluid swivel will be configured as follows:

Production:	2 x 10 inch
Production Test:	1 x 6 inch
Gas Lift:	2 x 4 inch
Gas Export:	1 x 4 inch
Hydraulic Control:	8 x 1 inch

The swivel assembly will also incorporate an electrical swivel for power, controls and communications.

The design production rate is 35,000 barrels per day with 35 MMCFD gas export.

The FPSO will be moored with a symmetrical six leg composite wire/chain system and high capacity drag embedment anchors. The proposed mooring for Barracuda may also incorporate a single intermediate support buoy in each leg. This type of "inverted catenary" design provides the same advantages noted previously.

EXTERNAL TURRET SYSTEMS

Another type of permanent turret system which has become quite familiar within the offshore industry is the cantilevered external turret. The external turret represents an alternative design which is less expensive and which can be delivered in a shorter period of time compared to the permanent internal mooring. The external turret is equally versatile and can be mounted at either the bow or the stern of either converted tankers or new-built barges.

Although the external turret can be used in shallow to moderate water depths, the governing condition which limits applicability of the external turret is generally the maximum mooring load resulting from either extreme environmental conditions and/or deeper water depths.

Following are two additional examples of actual ongoing projects using cantilevered external turrets with equally challenging design conditions.

Project: **Shell Todd Oil Services**
Location: **"Maui B" Field New Zealand**
Water Depth: **114 meters (375 feet)**

The Maui B platform, located offshore Taranaki, New Zealand, is an unmanned satellite platform and has no gas, condensate or oil processing facilities. All wellstreams are delivered to the Maui A platform for processing.

As a result of recent discoveries in the area, the recoverable reserves and the associated need for processing capacity in the field have increased significantly. A floating production storage and offloading facility has been selected as the means for supplementing the existing field facilities.

Because of marginal economics and the need for developing a minimum cost FPSO, an external cantilevered turret will be installed on the 135,000 DWT converted tanker "Ellida" (FIGURE 8).

As indicated in the general arrangement drawing, the Maui B turret system is not only cantilevered far out from the bow of the tanker, but it is also significantly elevated, higher than other similar turret systems. Because of the high mooring loads resulting from the water depth and severe 10.7 meter significant wave conditions at the Maui B site, a fairly robust turret structure was required to carry the loads into the vessel. An elevated turret provided a more direct and efficient load path. The elevated turret was also necessary to avoid wave slamming loads from impacting the underside of the turret chain table.

A significant design challenge resulting from the severe weather conditions at the Maui B site was the need to optimize the anchor leg system for fatigue loading. While the wire rope and mooring chain of the anchor leg system is typically designed for maximum loads, it was recognized that the fatigue wave spectrum would clearly govern the design of the anchor leg components. An extensive series of model tests recently conducted at MARIN has confirmed that a ten leg composite wire/chain system will be required.

The combination of water depth, an external turret mounting, and a severe fatigue wave spectrum resulted in unusually high cyclic line tension variations at wave frequency. Fatigue resistance and good elasticity were then primary considerations in the design and selection of anchor leg components. Fatigue resistance of the wire rope main body is much better than that of stud link chains. The size and grade of the chain and connector components were then designed in consideration of the fatigue load spectrum. Unfortunately, sufficient fatigue data for higher strength chain grades such as K4 or R4 are not yet available to permit a thorough fatigue evaluation. Consequently, use of these higher strength chain grades in a fatigue driven anchor leg design may not be beneficial. In a wave frequency dominated system such as the Maui B FPSO, the requirement to use larger diameter, more standard grade chain components such as ORQ or R3 grades is somewhat self-defeating in that the larger chain further increases the wave frequency tension variations due to its greater weight and increased drag and inertial load contributions.

Serious consideration was given to the use of studless chain which holds great promise with respect to improved fatigue resistance and increased elasticity. The schedule for the project, however, did not permit an adequate evaluation of studless chain data which is now under development. An ongoing joint industry project, including SOFEC, Ramnas, DnV, LRS and ABS, investigating the strength, elasticity and especially fatigue resistance of studless chain is intended to culminate in the development of an international standard for studless chain. It is expected that studless chain will play a significant role in the design of anchor leg components for future FPS and FPSO projects.

The severity of the fatigue load spectrum also controlled much of the design of the wire rope spelter sockets and connecting hardware between the wire rope and anchor chain components. A thorough finite element analysis and subsequent fatigue evaluation is required for all connecting hardware. It is recommended that the fatigue evaluation be performed using a fracture mechanics based approach which correlates the assumed initial flaw size with the sensitivity of the non-destructive examination techniques employed in the manufacture of the related component.

Project: Chevron
Location: "Escravos" Field Nigeria
Water Depth: 28.5 meters (94 feet)

While deep water depths and severe environmental conditions certainly pose many challenges to the designer, in some instances very shallow water depths may be equally or even more challenging than similar systems, such as Maui B.

Development of the Escravos field offshore Nigeria will include a floating storage and offloading vessel for the refrigeration and depressurization of liquified petroleum gas (LPG). The LPG FSO will be a purpose-built barge moored with a symmetric 6 leg all chain mooring system.

As with the Maui B turret system, the Escravos turret is also cantilevered from the bow of the new-built barge in order to avoid interference between the mooring chain and the vessel's keel (FIGURE 9).

The environmental conditions off the coast of Nigeria are characterized by fairly benign wind, wave and current conditions, however, there is a fairly consistent swell along the coast which can frequently exceed 2 - 2½ meters significant for extended periods.

This maximum swell combined with very light associated wind and current creates a unique design condition. Because this environment provides for very little mean offset of the FPSO vessel, the relatively large swell-induced low-frequency vessel excursions in the upstream direction give rise to potential interference between the anchor legs and the FSO keel. The anchor leg configuration and outboard location of the turret must then be optimized to eliminate interference. Ideally, a fairly soft mooring with a low preload would be considered to maximize the separation between the anchor legs and the vessel's keel in still water conditions. On the other hand, since the maximum allowable excursions of the riser system in this shallow water depth are severely limited, the mooring system must also be stiff enough to limit the extreme FSO offsets.

Another interesting characteristic of the Escravos environment is the fact that the specified maximum operational conditions (5 year return period) are nearly identical to the survival conditions (100 year return period). This combined with the fact that the maximum offloading LPG carrier (80,000 cubic meters capacity) is even larger than the moored LPG FSO (55,000 cubic meters capacity) results in a situation where many of the design values are governed by the maximum operational condition.

In particular, extreme downstream offsets of the tandem moored vessels in maximum operational conditions can be even greater than the offsets of the FSO alone in survival conditions.

Consequently, the resulting anchor leg design involved a ratio of required weight to required strength that is somewhat larger than normally required for turret moored systems.

ACKNOWLEDGEMENTS

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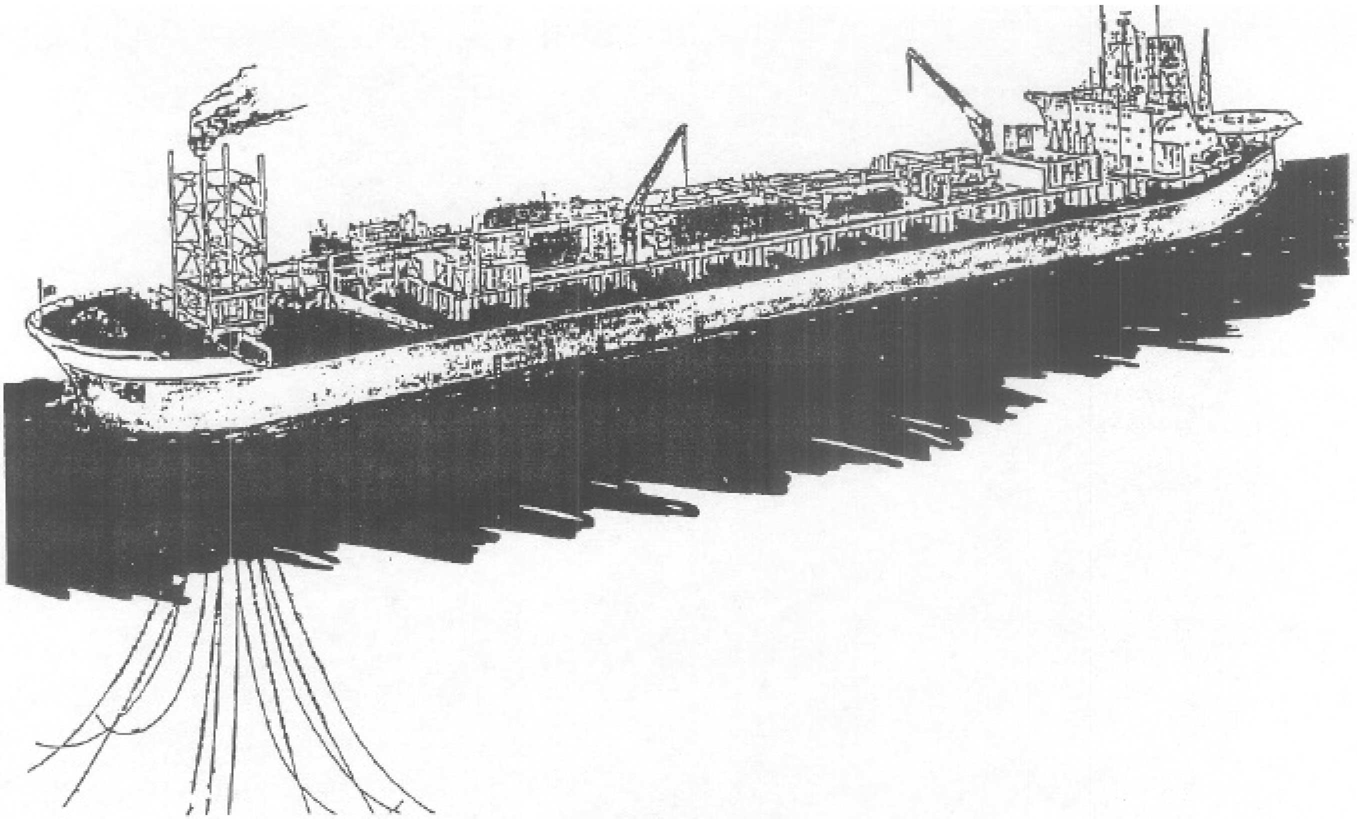

Fig. 1 Liuhua 11-1 Field Development FPSO

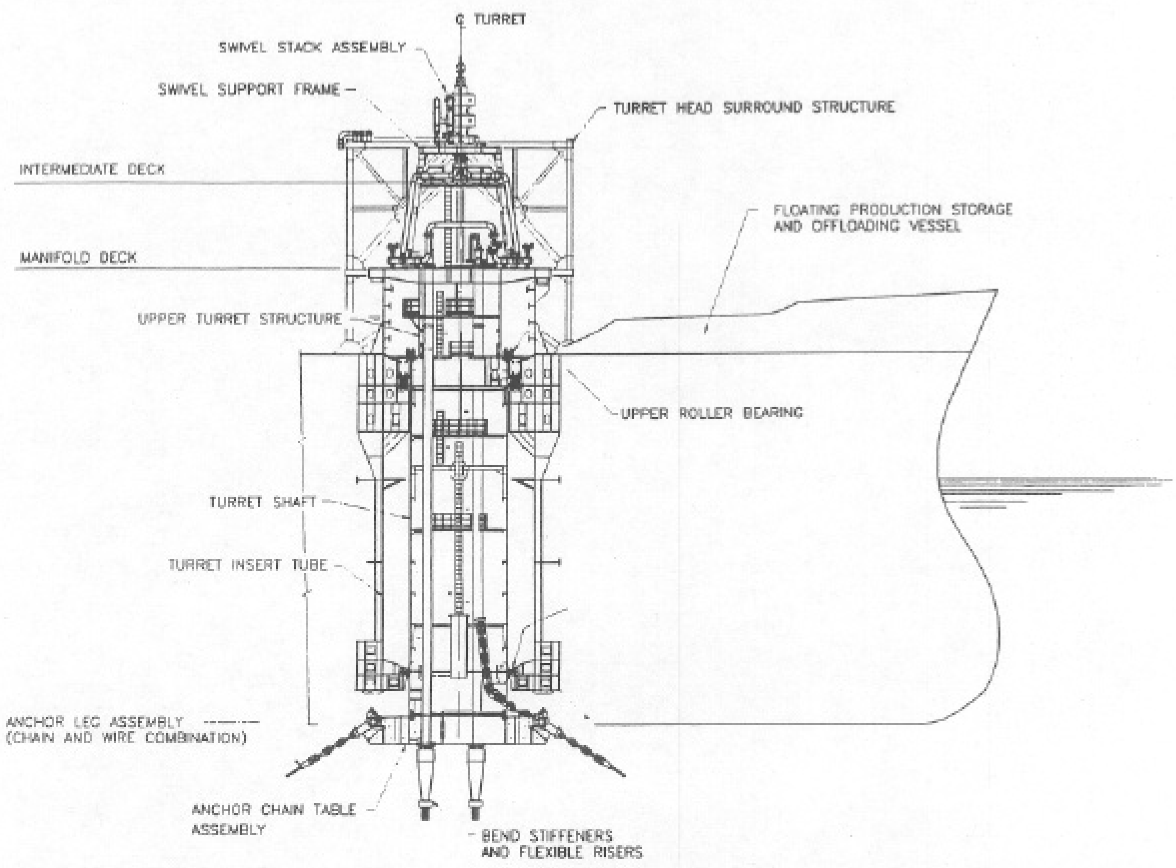

Fig. 2 Liuhua Internal Turret System

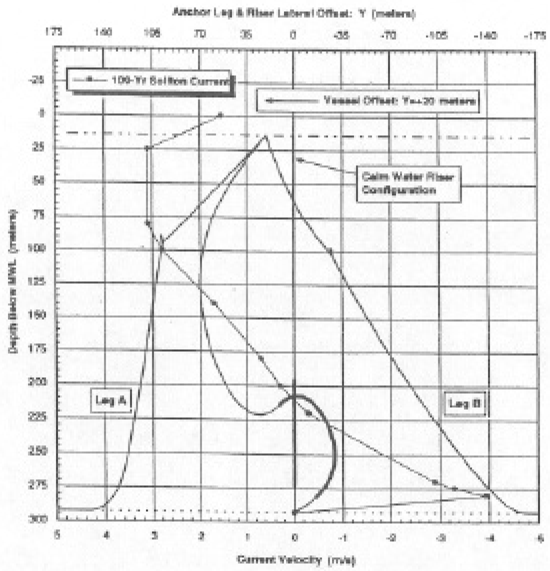

Fig. 3 Liuhua 11-1 Riser and Anchor Leg Configuration in Soliton Currents

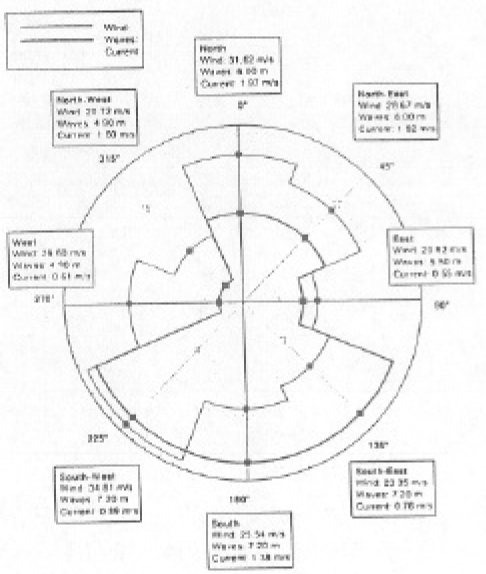

Fig. 5 Barracuda Design Environmental Conditions

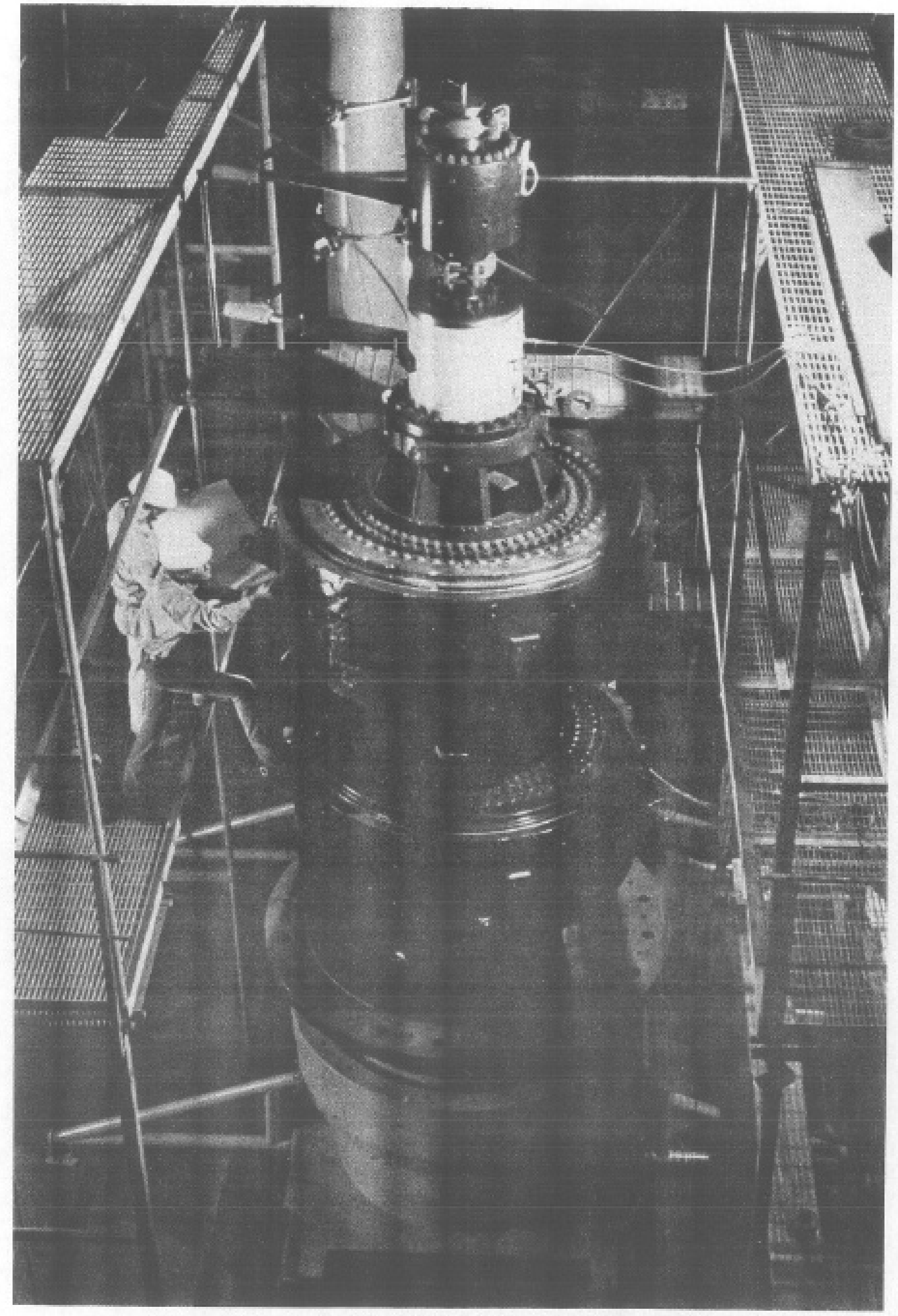

Fig. 4 Liuhua 11-1 Fluid Swivel Assembly

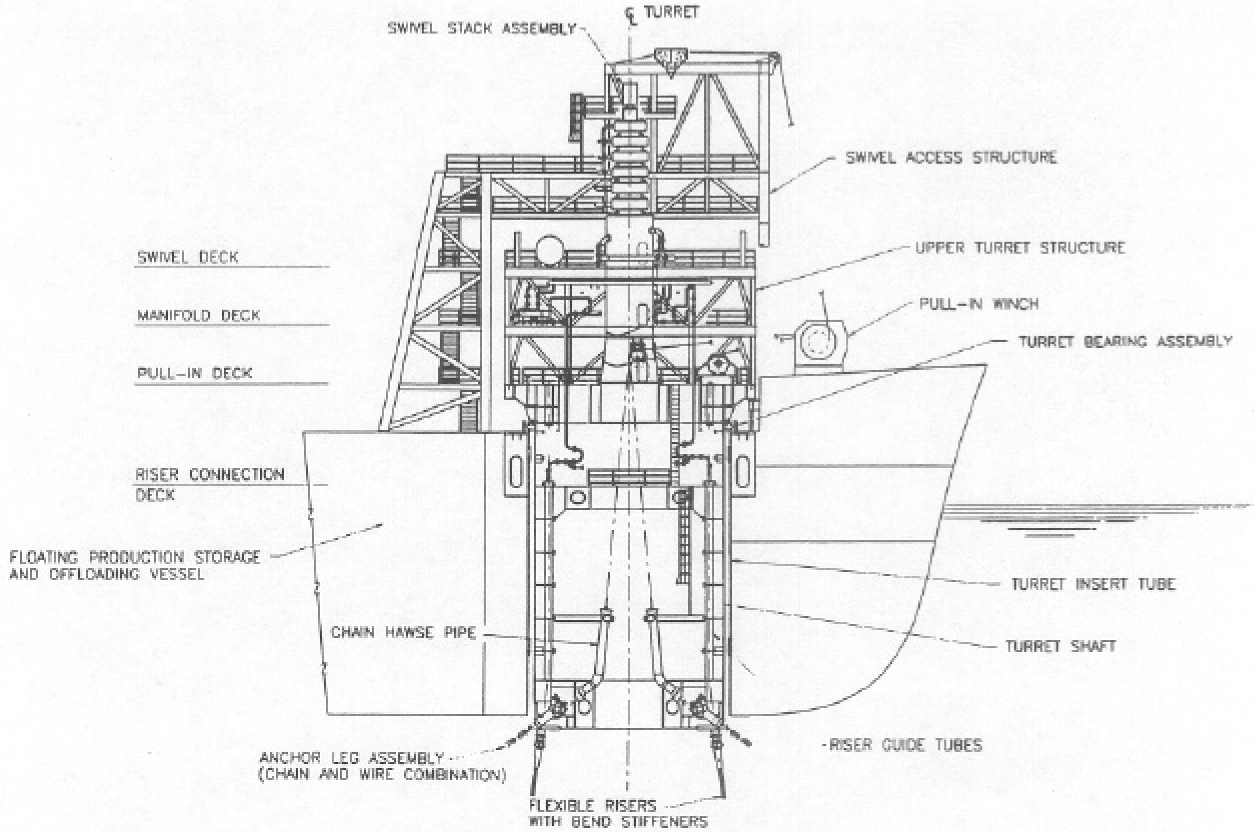

Fig. 6 Barracuda Internal Turret System

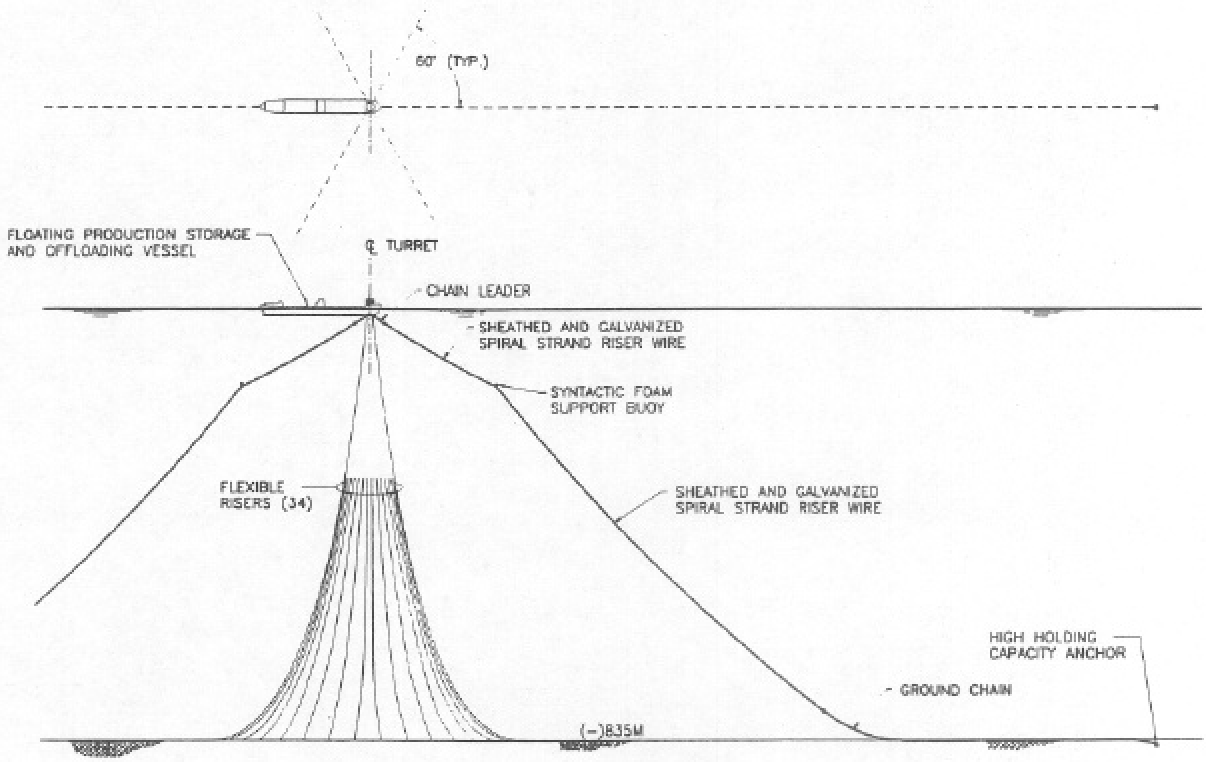

Fig. 7 Barracuda Field FPSO

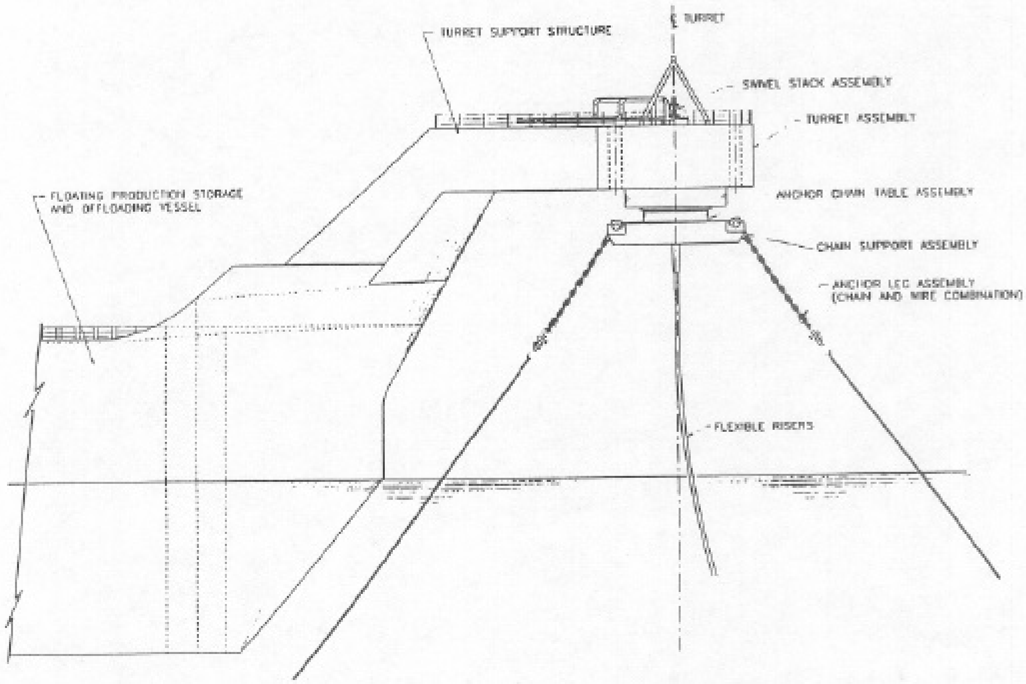

Fig. 8 Maui B External Cantilevered Turret

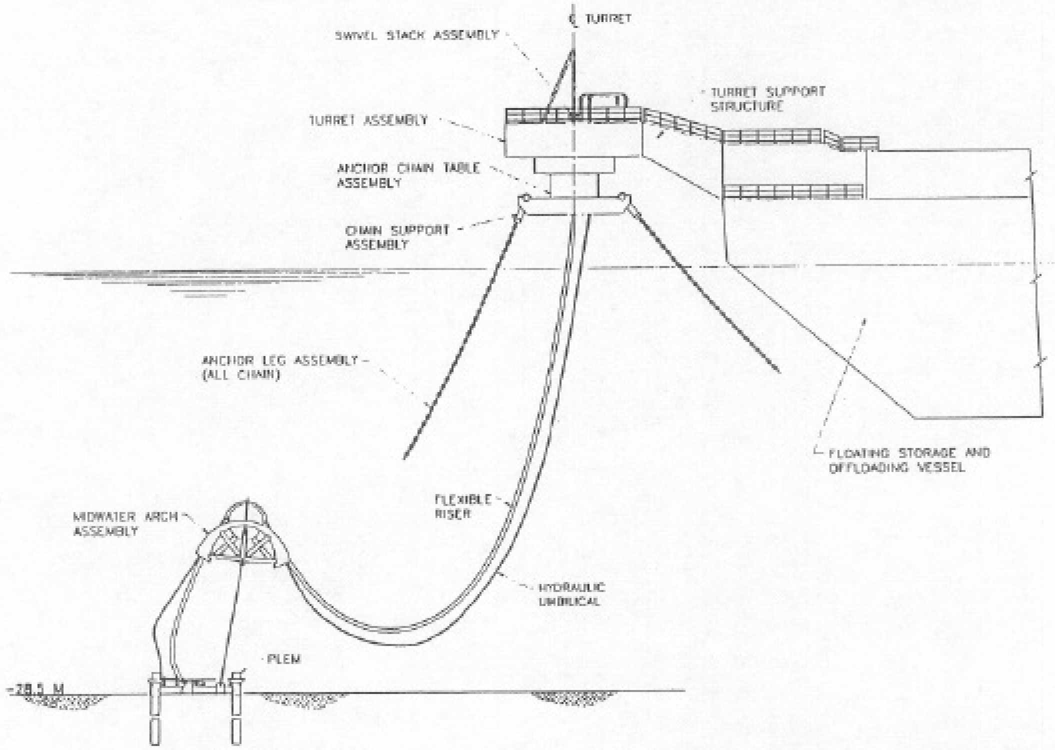

Fig. 9 Escravos External Cantilevered Turret