Design and Installation of a Production Jack-up with Storage

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ABSTRACT

Many techniques, mostly coming from the mobile offshore arena, combine to create with the MOPUstor design a new concept combining oil-storage and oil-production in an economic self-installing package. The completed SIRI project shows that this type platform can be designed, fabricated and installed in a very short time even for North Sea conditions.

INTRODUCTION

In February 1996, a STATOIL led group decided to develop the SIRI-field in Block 5604/20 of the Danish sector of the North Sea as a stand-alone, re-usable, production-storage platform in a fasttrack program. The considerations, leading to this decision and to the selection of Kvaerner with the MSC-MOPUstor concept for the EPCI contract, have been described in a paper for the 1997 City University Conference. Figure 1 shows the platform concept, a production jack-up fixed on top of a steel storage tank.

The present paper will highlight the less usual aspects in the design and engineering of this self-installing platform. Before focussing on the structure and the installation aspects, it is worthwhile to point to the contractual set-up as the most important factor that enabled the realization of a non-traditional concept in the very short time schedule.

- The contract was based on a functional specification that was timely available and which was never subject of dispute.
- Competition was introduced by starting the process by a partly paid three month long design competition with three parties, ending with one being assigned the task of completing the design-fabrication part in 20 months.
- Responsibility for the fulfillment of the functional specification was entirely with the main contractor.
- All parties were, by contract, motivated to come to the lowest cost solution that met the specification.
- The involvement of the same people and companies from concept to completion made it possible to evade extensive intermediate documentation, approvals periods and transfer of responsibility.

For general reference, the platform specification is given in table 1.

Environment	
Water depth	60 meters, 65meters dredged
100 year wave	25.7 meters at 15 sec
Current	1.25 m/s at surface
Wind (10 min mean)	39.5m/s (at 10m)
Production Capacities	
Max oil production	8000 Sm^3/day
Max water production	11000 Sm^3/day
Max liquid production	12000 Sm^3/day
Gas compression	1.1 M Sm^3/day
Water injection	13000 Sm^3/day
Storage and Offloading	
Storage volume	50000 m^3
Offloading rate	2500 m^3/hr
Topsides	
Deck weight	11000 t operational
Gross area	2800 m^2
Accommodation	60 men (single cabins)
Work-over	400m^2
Wells	
Number of slots	12 (6 drill, 3 injector, 3 spare)
Arrangement	in a 4.65m circle

Table 1: Main data for field development

THE FASTTRACK SCHEDULE

The milestones shown in table 2 show the realized schedule; this followed the ambitious planning until the tow-out date of the jack-up deck. This meant that the very tight design and fabrication schedule of 20 month was met with no day to spare.

The installation and subsequent hook-up and commissioning took longer than planned; the main cause of this chain of events was October as the first installation month possible. October and November have few and an infrequent good-weather periods, which make that the best possible schedule differs greatly from an average schedule.

The successful installation attempt, after seven weeks, coincided with a massive move of mobile units in the North Sea, which all had been forced to wait the same time for this good period. This at least showed that the production jack-up was on par with the mobile units for what concerns installation limits.

Milestone	Actual date	Remarks
Letter of intent	1 /2 / 1997	Tank changed from 80000 to 50000 m^3
MTO deck	20/2 / 1997	
MTO tank	3 /4 / 1997	
AFC drawings deck	5 /5 / 1997	
First steel cut deck	20/5 / 1997	
AFC drawings tank	26/5 / 1997	
First steel cut tank	1 /11/ 1997	
Float-out tank	20/2 / 1998	
Dry-tow tank	15/3 / 1998	Tow from Korea to Stavanger
Wet-tow tank	7/5 / 1998	Tow from Stavanger to SIRI
Installation tank	16/5 / 1998	
Float-out deck	1 /4 / 1998	Lifting of jacks, modules
Lifting Legs, Flare tower	6 /7 / 1998	
Wet-tow jack-up deck	1/10 / 1998	Planned date 1./10/1998
Deck Installed	19/11/ 1998	
First Oil	1 /3 / 1999	

Table 2: Project milestones

INNOVATION OR TECHNOLOGY TRANSFER

Innovation is often touted as a competitive advantage. This is misleading; innovation is only an advantage after it has proven to work. It is, in other words, only an advantage after it has stopped being an innovation. For first-time users, innovation is an unavoidable element that needs to be compensated for by an otherwise unachievable economic advantage.
The number of innovations used in the design of a platform is therefor a good measure of the marginality of a field development.

This platform, though innovative for a production platform, is more aptly called an example of technology transfer from the world outside the fixed platforms. Still, each innovation needed a direct effect on the field development cost to become acceptable to the project. The cost benefits came from:

A low-weight tank; fit for dry-tow transportation completely ballasted
A pre-drilling structure that is a functional part of the tank
A post-installed jack-up built with low-cost legs and jacks.

Technology transfer

- Tank on a skirted plate foundation, installed by suction
- Deep dredging to expose the foundation layer
- Soft, “ambient pressure” tank design
- Straight tubular legs without welded attachments or inserts
- Redundant jacking systems, capable of lifting the deck after failure of a major component such as a lifting cylinder or a jacking pin.

Innovations

- A well-caisson integrated in the tank which, as a stand alone structure, acts as the predrilling structure for surface completed wells
- Leg-tank connection by grouting

These innovations not only survived because of cost advantages. There also was sufficient confidence in the elsewhere-demonstrated concepts to accept conclusive proof as part of the final documentation. Without confidence in concept and execution, the combination of fasttracking and innovation easily becomes a dangerous mix. The time lacks to execute the engineering in safer, sequential steps. Doubt, when it surfaces, must be dealt with immediately by an open-book engineering attitude.

THE JACK-UP LEGS

The three legs of the production jack-up are straight tubular without any internal stiffeners, bulkheads or inserts. The wall thickness ranges from 110mm to 65mm. The climbing mechanism is by pins in flame-cut holes. The use of material with a minimum yield of 690N/mm^2 is dictated by the wish to take the contact forces between pins and leg without welded inserts or reinforcements. The strikingly slender legs are made possible by the reduction in free leg-length through the raising of the bottom (tank roof) and the full fixity in the tank and at the deck. The allowable leg-length of an independent leg jack-up with the same leg size would only be 50m, not 70, the sum of air gap and depth to the roof for SIRI.

What seems to be the fourth leg is in fact the well caisson, containing 12 well slots in a circle with 1000mm center to center spacing. The caisson does not support deck weight but it follows/resists the horizontal deck motions just like the legs. The stiffness of the 5.25m caisson, bending in cantilever mode, is similar to the stiffness of the legs, bending in an S-shape. See fig 2.

The Main Tubular

The reason for the straight tubular is primarily cost. The reason for the rejection of welded attachments is to keep all structural details as fatigue resistant as possible. The worst fatigue life is found in the circumferential weld which, when not ground, belongs to the "D" fatigue curve. Holes for jacking or attachments (see fig 3), made in parent material only, belong to the "C" curve.
An unfortunate fact is the need for a smooth leg outer-surface to better help the legs slide through the guides. The flush outer surface makes for an SCF larger than 1.0 at the inside of the tubular leg at a change of wall thickness. Offsets in plate centerline between the rings that make up a leg are also given a tight tolerance to keep another contribution to the SCF down. The lowest fatigue lives are consequently found at the wall thickness change closest to the clamped ends of the legs. See fig 4.

The Holes

There are three jacking holes of 460mm diameter per cross section. Cross sections are distanced 1.75 meter apart. The open leg is used to locate seawater pumps and sumps. This protects the pumps from the wave forces and reduces the total drag on the platform.

The lowest part of the leg, which is fixed in the tank, is left without holes. This means that the leg, when engaged by the jacking system in the lowest hole, sticks 16m below the deck bottom.

Installation of the Legs

The three, 105m long, 800 ton legs were transported in one piece from a fabrication yard in Holland to the Kvaerner yard in Stavanger and lifted-in by two large shearlegs in a parallel lift operation. See fig 5.

Fixity in the tank

The legs are given full fixity in the tank by inserting them in 13m deep sleeves and grouting the annulus. The full vertical load is taken at the bottom and the grout merely served to fill the horizontal gap between the leg and the support rings at the top and bottom of the sleeves.
The caisson is grouted in a similar manner in its sleeve.

The Leg Fatigue Analysis

The legs fit very closely in the jack house guides; the guide radius is only 5mm larger than the leg outer radius of 1750mm. This is less critical for the installation of the legs than it seems, the leg circumference is precisely controlled and the cross section, even when not circular, is flexible and shapes itself to the guide.
The small gap still plays a surprising role in the fatigue analysis of the legs. The gap makes the mass-spring system of deck and legs acts as a soft spring in the vertical (center) position. It becomes stiffer when some deflection forces the legs into contact with both jack-house guides and thus forms a beam clamped on the tank and the deck side. The gap makes the response of the deck to external forces non-linear and more importantly, the soft section is right in the center were the bulk of the small waves contribute most to the fatigue life.
The pre-design of the legs included a full stochastic fatigue analysis. Time-domain simulations were used to get the platform response to a random wave spectrum from all directions. This analysis was later redone including the non-linear behavior and rigidity over the gap as the additional parameter. See fig 6 for the effects on the fatigue life. The design was tuned to the rigidity that resulted in all fatigue lives being above 60 years.
This intensive analysis effort also showed that the modeling of directional wave spreading needs a perfect randomness to prevent small energy density differences between the leg positions. These small differences are amplified by the fatigue life calculations in a way not found with larger structures that get load contributions from more than one point of the random sea surface.

JACKING SYSTEM

The jacking system is a step-by-step hydraulic system. This system is in use on all of the smaller, closed leg MSC jack-ups. It is different in holding capacity, 5600 ton, about twice the largest built to that date and in the way, it was arranged to meet the particular requirements of redundancy and holding capacity for this job. See fig 7.

Full redundancy

The single-failure acceptance philosophy, normally applied to the power units and the controls was extended to include failure of a main jacking cylinder or a jacking pin. This could be done with relatively simple means because the jacking ring is an assembly of three completely self-balanced sections. De-activating the section with the failed element leaves two-third capacity to finish the operation, be it with a lower safety margin.

Holding capacity

The jacking systems are utilized to fix the deck until it is reactivated in six to ten years for removal. In the holding mode, it needs to resist the loads from the 100-year survival condition. This is a normal condition for jack-ups; not normal is the extreme vertical load due to an explosion on the deck. To handle both extreme loads the jacking system is arranged to engage the jacking pins of both rings at the same time at any final elevation. The jacking system is made passive (not depending on hydraulic pressure or clamping loads) by shimming the jacking cylinders. The even load distribution over the two rings with three pins per leg is assured by elastomer blocks that support the rings.

SUBSEA TANK

To design a tank with a low steel weight and thereby low cost, it is necessary to:

- design for low pressure differentials over the tank walls
- design for a low ballast weight
- design for a light foundation structure

Low Pressure differential

The oil-water displacement principle is an important element to achieve a low pressure-differential over the walls during the operational phase. Temporary phases may spoil that gain and it is vital to limit that impact by design. The pressure differential from all contributions (oil specific gravity, wave pressure, pumping pressure) could be held below one bar. About 75% of the tank structure are designed to this low pressure.

The remaining 25% of the volume of the tank are designed to withstand the six bar bottom pressure and to serve as buoyancy tanks during the installation. Early in the project, the decision was taken not to use disconnectable buoyancy tanks. This decision was based on:

- the unpredictable costs and availability of loose tanks
- the complications and risks in the marine operations
- the complication of reinstalling loose tanks for removal and re-installation

The best estimate for the cost associated with the internal buoyancy is the cost of 800-ton steel that could have been saved on the tank weight. At the cost of 2.4 M$ for 800 ton steel 15000 ton reusable and manageable buoyancy is obtained. See fig 8.

The single biggest disadvantage of the integrated buoyancy tanks is that they need to be joined to the main tank for the operational phase when a single storage volume is mandatory for simplicity of storage management. After the installation of the tank, an ROV is used to open the valves in the piping that connects both the water and the oil phase to the main storage compartment.

Low Ballast Weight

The ballast weight can be needed for on-bottom weight, on-bottom sliding stability and installation stability. To keep the ballast weight low it is necessary to have:

- no static up-lift in the operational condition
- sliding resistance based on soil cohesion (clay) rather than friction (sand)
- a low Vertical Center of Gravity
- a high Center of Buoyancy
- small free water surfaces during installation

The “no-uplift” excludes having “dry” oil storage, the oil/water displacement storage needs no ballast to supplement the minimum design weight.

The installation stability of the structure with the caisson reaching 80m high above the tank roof was the item deciding the amount of ballast needed. 5500 ton was installed at the yard in Korea and dry-towed to Stavanger. The back-up possibility to add ballast before the wet-tow to site was not required.

Light Foundation Structure

Having no ballast requirement for the foundation is the biggest step to a light foundation structure, but the clay foundation layer is found at 5m below the mud line. The top layer is partly sand and soft clay. To reach the foundation layer two options exist:

- Long penetrating skirts
- Removing the top layer by dredging

The first option would lead to at least 2000t additional steel, a serious skirt penetration problem and draft problems at float-out and loading onto the transportation vessel.

Dredging to 65m depth was made possible by a number of new vessels capable of dredging to this depth that became available the last two years.

Tank Weight

The final tank weight was 8000t (excluding the caisson but including the skirts) for a 60000m^3 tank with 50000m^3 effective storage capacity. The 10000m^3 loss in storage capacity is due to the mentioned internal ballast, provisions for a sludge layer at the oil-water interface and a permanent buffer volume with water at the water in-out let.

THE OFFSHORE INSTALLATION

For any self-installing platform, ease off installation is a property of the structure. Installation design must therefor be an integral part of structural design activity and of the structural design responsibility.
The equipment deployed for the installation and the way the installation is executed in terms of safety, for the vessels and the crew, are the responsibility of the installation contractor. The installation scenario to follow was defined by MSC, including the bandwidth of the control variables that still assured a safe structure.

The tank remains, after installation, half a year without the jack-up deck. This does not require additional measures to assure a stable foundation.

Subsea Tank Transportation

The tank is dry-towed on a relatively small vessel from Korea to Norway. It is supported on the skirts on wooden stoppings and refrained from sliding by directly connecting the skirts to the deck. See fig 9. Close to the field, in Stavanger, the tank is unloaded and towed with a freeboard of 13 meter to the site by two tugs and one trailing tug. The tank with the 85m high well caisson is highly stable and has no real weather limitations. See fig 10.

The Tank Installation Method

POSITIONING
On location, the two front tugs are moored on prelaid anchors lines, while the aft tug applies a constant pull to determine the heading of the tank and stabilize the mooring triangle. The two front tugs use their winches to get the tank on the desired location.

INSTALLATION BY BALLASTING
The ballasting operation is remotely controlled from a fourth installation vessel. The temporary installation equipment (power, pump and valve controls) is contained in a subsea electric/hydraulic module. This module is connected to piping at the base of the tank. An umbilical connects the subsea module to the control module on the installation vessel.

The ballast operation starts with the free flooding of the main volume and the subsequent topping up of the part that still is above sealevel.

Next, the three buoyancy tanks are partly filled to submerge the roof. This part of the operation is the most critical, since the tank needs a precise trim position, just before submergence of the roof, to float level in submerged condition. The crux of the submergence is that any trim deviation from the ideal position is multiplied many times, when the GM drops from 23 meter to 0.6 meter. There is no possibility of capsizing; the tank is stable in any inclination angle. It is the slow trim response of the heavy (filled) tank to over-ballasting on one side that can lead to erroneous determination of the equilibrium trim angle. The trim angle is constantly monitored to one hundredth of a degree accuracy, but the progress of the submergence of the tilted roof cannot be measured. This observation of the roof submergence (and the progress in reduction of the GM) requires quiet sea conditions. Motions due to waves are small and not the reason for a quiet sea. See fig 11.

After submergence of the roof, the depth of the tank is controlled by the buoyancy of the well caisson. Filling the caisson with one-meter of ballast water lowers the tank by one meter. This is the ideal way to lower a tank and one of the reasons to favor the tank caisson integration. Ballasting of the caisson and positioning by the tugs continues until the skirts touch the bottom. After stabilizing the tank on the skirts, the position is verified before completely filling the buoyancy chambers to penetrate the skirts. With sufficient penetration under weight alone, suction is used to penetrate to target depth. The separate compartments of the skirt area are used to level the tank by applying suction selectively on the high sides. This was done so successfully that the trim indicator (0.01 degree accuracy!) showed zero.

GROUTING
The remaining gap between bottom and seabed was, compartment by compartment, filled with grout taking good care to keep the lines open for later removal.
The last step in the installation operation was pouring a grout layer in trays on the roof for tank impact protection.

Weight Control

METHOD
It will be clear that maintaining the GM value above a minimum of 0.2m requires careful weight control. It is a fact that an inclination test in a very stable (high GM) condition will not provide the accuracy needed to determine a very low GM value. Arranging a low GM value as a preliminary to the inclination test means either doing the submergence before knowing the GM or adding the large ballast quantities and thereby introducing unacceptable errors. A combination of weighing and calculating is the only means to know the GM with sufficient accuracy. The method followed was to first weigh the most critical items (the caisson parts and the ballast introduced at the bottom) and subsequently weigh the total structure in the flooded dock by draft measurements. All measurements, calculated values and estimates, with the

accuracy of the method of determination, were combined in a procedure that calculated the worst and best possible GM within those constraints.

RESULTS

The worst possible GM-value, before the displacement test, was 0.2m with the planned ballast of 5000t. It is a tribute to the simplicity of the structure and the fabrication control by the Daewoo yard that the fabricated weight was off only by 30 tons. This lifted the worst possible GM after the displacement test to 0.4m. The additional 500t that could be added to the transportation weight now that the weight was on target lifted the minimum to 0.6m. This value proved to be consistent with the inclination response shown during the actual installation.

Jack-up Deck Transportation

TRANSPORTATION CONDITIONS

The fully outfitted deck was wet-towed to the SIRI site by two 120-ton tugs in front and two 60-ton trailing tugs. The total towing–installation time made it impractical to execute it in a 72-hr weather window period. It was therefor necessary to design for the following:

- Survival with possibly major damage free drifting in a100-year storm condition
- Survive the 10-year October storm in stand-by mode with minor damage only
- Unmanned tow of the platform.

SEAWORTHINESS

The hull with a depth of 6.7m was laid out for a freeboard of 3.0 m. A continuous dialog was maintained with the layout group to limit the use of cantilevered platforms and design the inevitable ones fit for transportation. Model testing and motion calculations were used to optimize the deck for the highest protection during transportation by installing fit for purpose temporary structures. This resulted in a towing limit of H_S= 2.0m from all sides and the 10 year October limit (H_S=8.75m) from the bow +/- 45 degrees. See fig 12.

The fore-end of the deck was the submerged fork that, eventually, connected to the well caisson with the blast wall between the well area and the process area serving as an elevated bow structure. Speaking of this structure as having a bow is misleading; it is just a lumpy box with a slenderness ratio of 1.2, hardly a naval architects dream.

The well manifolds, supported on the forks in front of the bow required a special treatment. The manifolds were already half-submerged in dead-calm conditions. The solution adopted to cope with the 10 year waves coming head-on was to lift the manifolds with their connecting piping as a complete package over 8.0m along vertical guide pipes within the existing manifold structure. See fig 13.

The aft part was vulnerable by having the living quarter cantilevered over the stern by 7m. This was one issue were layout prevailed over transportation considerations.

TRANSPORTATION RESULTS

The installation operations provided an unwanted but nonetheless valuable full-scale test for the seaworthiness of the deck. It was twice towed back over 150 miles in deteriorating weather. Observations during the tow were not possible; there was no crew on board and observations from the tugs were made impossible by the heavy spray generated by the blunt bow. Inspection afterwards confirmed however the capability to be towed in conditions up to 4.0m $H_{S,}$ at a speed of 5 knot, with no damage to structure or equipment.

Installation of the Jack-up Deck

POSITIONING

The mooring arrangement for the deck was the same as for the tank; two lead tugs moored on prelaid anchors with the two small trailing tugs pulling the mooring triangle tight. The two mooring wires ran one on each side of the well caisson with the drilling jack-up that remained in position. The fork with the well manifolds was wide enough; to allow first-order wave motions without contact between the fork and the caisson. Of course provided that the average fork position was not changed by the tugs.

MATING DESIGN

The mating operation of the jack-up legs to the tank contained three critical stages, separated by a less critical waiting position.

- Entering the legs horizontally in the guides and stopping lateral motions of the legs
- Pulling the legs to the end of the guides (stop longitudinal motion) and lowering the legs vertically in the cones on the sleeves
- Set the legs down on the bottom of the sleeves and lift the deck free from the water.

With the help of time-domain motion simulations, which were calibrated by the model tests, each phase was analyzed. The results were used to make each phase of the operation equally critical by upgrading the ones that were lagging.

- The guide structure was upgraded to withstand the maximum load acceptable to the legs
- The pull-in load to the end stops was determined such that once contact was made, it remained in contact
- The vertical interface between the legs and the tank was provided with a spring element to limit the contact loads to the jacking system capacity.

After these structural improvements, the environmental limits for the three steps were near equal. With the last two steps taking less time, the actual situation was that once step one was possible, the other steps were certainly possible.

THE MATING OPERATION

The actual conditions of the installation showed again that seastate information is not enough to define installation limits. The wind driven waves were low but a persisting swell, with a period close to the natural period for roll and pitch, forced the installation to pause until the period went below the calculated threshold. Figure 14 shows an example of a threshold graph. The threshold could be determined accurately by using the measured heave dynamic amplification to determine the swell period. The directly measured motions, that would have been more convenient to use, had proven in the simulations to be representative of only a, varying, part of the contact loads.

The subsequent very smooth mating raised the question if it could have been done under worse conditions. No definitive answer is possible but the mating was designed to keep contact loads out-of the impact load range. The shocks, most people were waiting for, would only have proven that limits were violated.

GROUTING THE LEGS

With the deck at the final elevation and connected to the well caisson (“fourth” leg contributes to the stability), the legs are grouted by filling the leg sleeves from the bottom up over the full 13m height.

REMOVAL

The structural removal of the platform consists of the following steps:

- Reactivate the jacking systems
- Disconnect the well caisson from the fork
- Disconnect the equipment in the legs from the deck
- Fill the buoyancy chambers with air

- Connect hoses to pressurize the skirt compartments with water
- Lower the deck into the water until positive pull is generated
- Pressurize skirt compartments
- Lift the tank as high as possible (draft approximately 30m). See Fig. 15.
- Tow to fjord for further decommissioning and refurbishing

The stability of the deck-tank assembly with air filled buoyancy chambers is such that air filling a part of the main tank can be considered. The buoyancy tanks however are large enough to neutralize the weight of the tank and the legs.

APPLICABILITY

The application of the MSC-MOPUstor concept on SIRI certainly showed that it fitted the field requirements. It also showed that the technology used to design and install the platform was capable to deliver the answers for this new application. Of interest is to know how far the concept can be extrapolated to smaller and to larger water depth, as well as to other soil conditions.

MAXIMUM WATERDEPTH

Project related feasibility studies have shown that above 90 meters a change over to lattice-type legs is economical. With lattice legs, particularly when tank and deck are installed as one unit, the limit extends to 150m.

MINIMUM WATERDEPTH

The minimum water depth is only related to the foundation stability of a voluminous tank in shallow water. In high wave conditions, there are no alternatives, which makes an economic cut-off impossible to define. A design for 40m depth with a 21m maximum wave and 50000m3 storage was shown a competitive proposition.

SOIL CONDITIONS

The most efficient designs are possible on clay soils, but on cohesionless soils such as thick sand layers it still makes economic sense to use minimum steel weight and high specific gravity ballast to replace concrete.

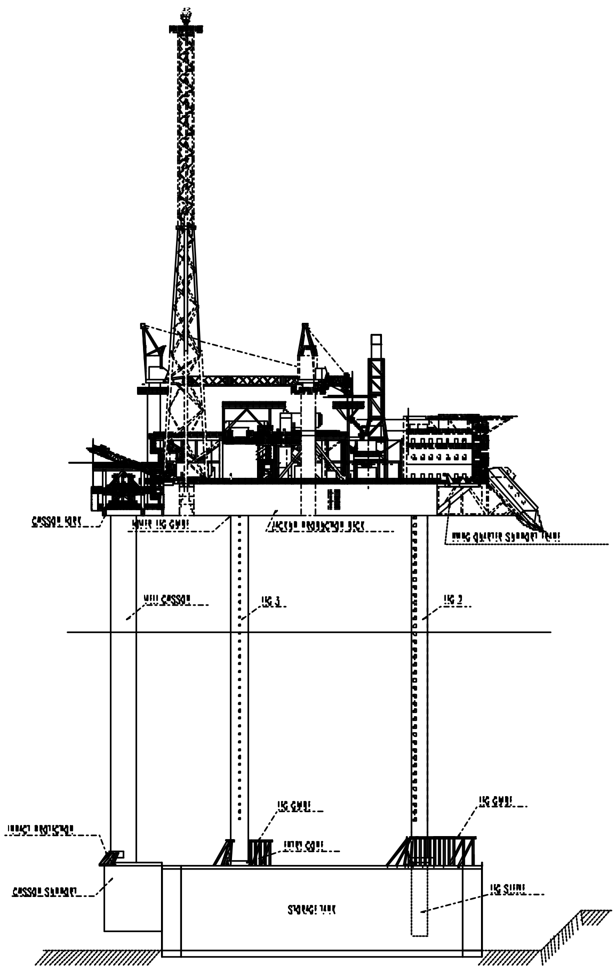

Figure 1: Side view of platform

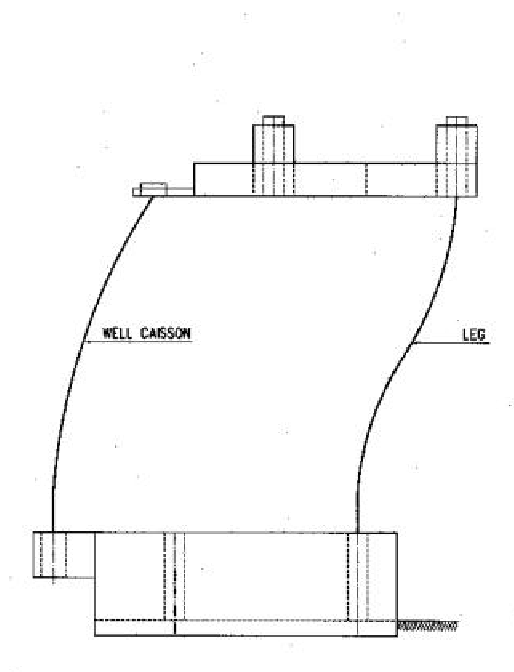

Figure 2: Leg deflection

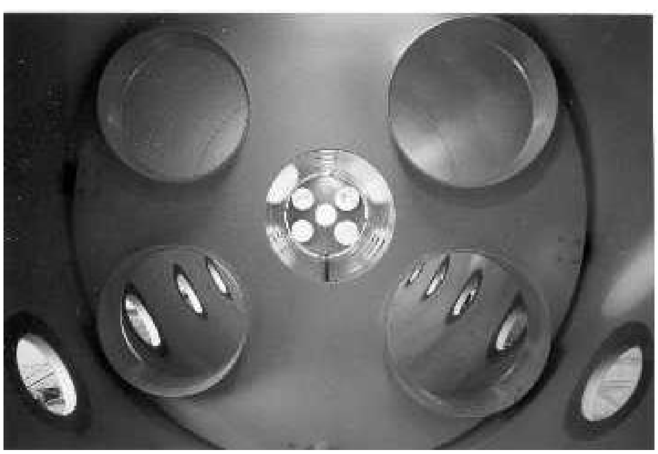

Figure 3: View inside leg

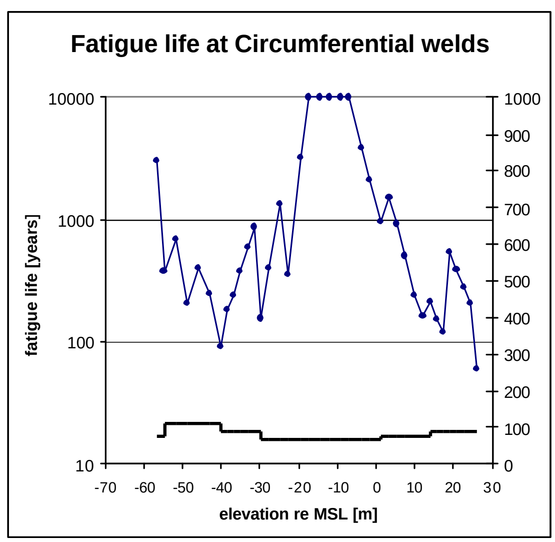

Figure 4: Fatigue life in legs

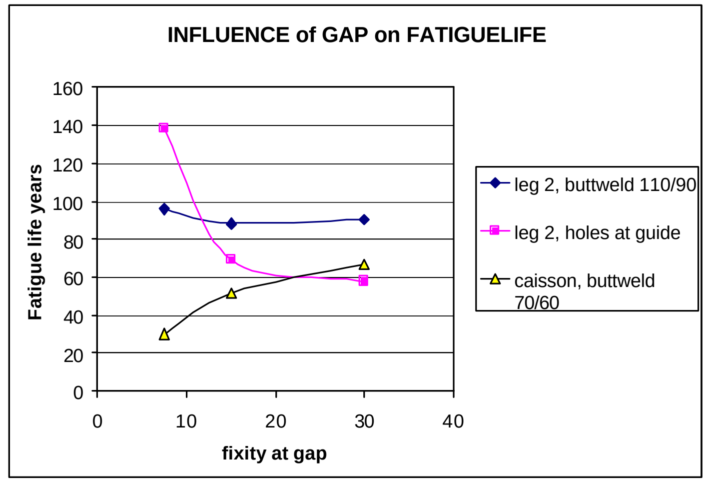

Figure 5: Lifting of legs

Figure 6: Fatigue life change with fixity at gap

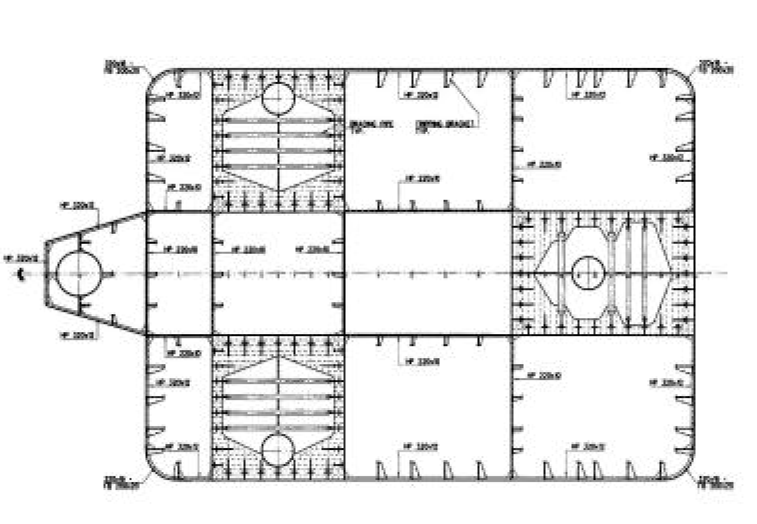

Figure 7: Assembly jacking system in jack house

Figure 8: Location of the three buoyancy tanks

Figure 9: Dry transport of ballasted tank

Figure 10: Wet tow of tank

Figure 11: Roof of tank being submerged

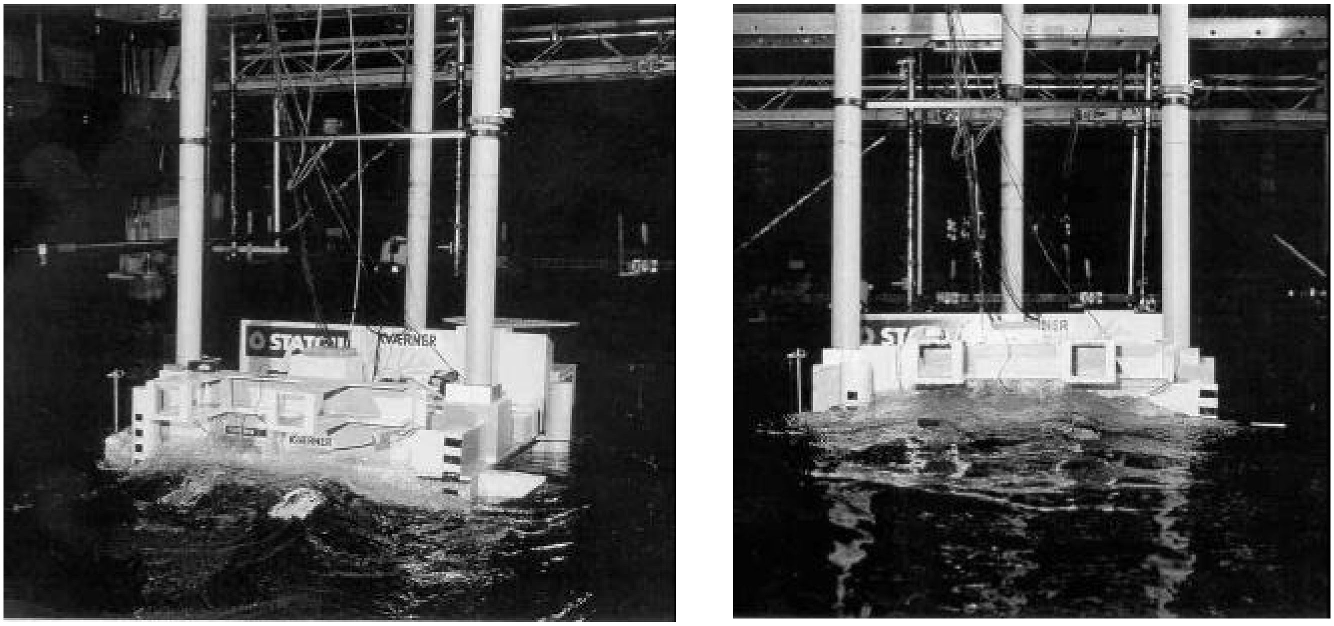

Figure 12: Model test H_s = 5.0 m head-on

Figure 13: Elevated manifolds

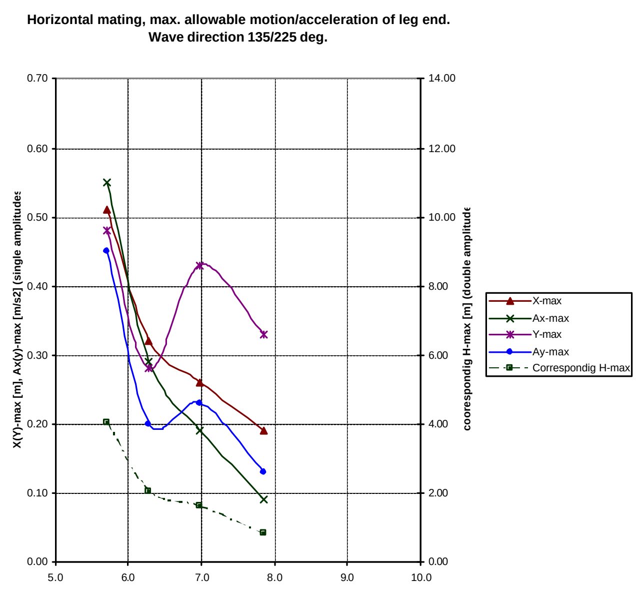

Figure 14: Mating limit graph

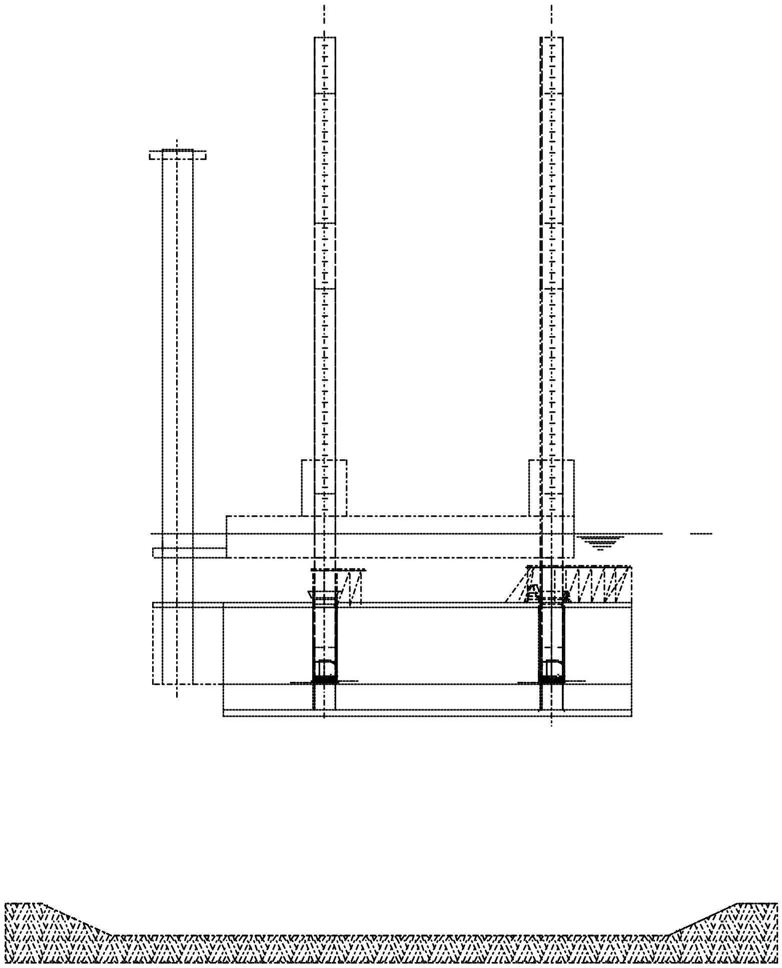

Figure 15: Removal configuration