Seven Years' Experience With the First Deepwater SALM

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Summary

This paper describes the performance of the Tembungo single anchor leg mooring (SALM) tanker loading terminal during its first 7 years of operation. This facility, located in 300 ft (91 m) of water, 50 miles (93 km) offshore Sabah, East Malaysia, has been in continuous service since Oct. 1974. It was designed to moor a 94,000-dead-weight-ton (DWT) (85 000-Mg) storage tanker permanently in maximum wave heights of 39 ft (12 m), winds of 65 mile/hr (29 m/s), and 2-knot (1-m/s) currents.

The Tembungo SALM has performed very effectively since start-up. Operational efficiency rates of up to 99.4% on an annual basis have been achieved, with an average of 95%. A major factor in the high utilization of this terminal has been the very low level of maintenance required on the SALM components. Planning the annual inspection and maintenance program with the diving contractor and developing detailed procedures for tanker change-out and for hose and hawser replacement were also important factors in maximizing operational efficiency.

Introduction

In recent years the petroleum industry has accepted the concept of using a single point mooring (SPM) as an integral part of an offshore production facility. The SPM, which provides direct tanker loading, may allow a field to be brought on-stream earlier than with a pipeline to shore, and it may allow the development of those fields having insufficient recoverable reserves to justify a pipeline. The Tembungo SALM is a good example of an early production application (Fig. 1).[1,2]

The SALM is located 7,000 ft (2134 m) from a fixed separation platform and is connected to the platform by a single 10-in. (254-mm) pipeline. While the SALM was designed to moor a storage tanker permanently that would be offloaded periodically by shuttle tankers moored alongside, it has been used only for shuttle service to date in an operation involving two dedicated 50,000-DWT (45 000-Mg) tankers that each load for 30 to 60 days.[3] While one tanker is loading, the other tanker departs to discharge its cargo. In this service, with prolonged periods of berth occupancy, the two shuttle tankers effectively become temporary storage facilities. This type of operation requires periodic production shut-in while the loaded tanker departs the SALM and the empty tanker comes on. These operational procedures have proved effective for producing this field and should be equally effective in the production of other similar fields.

System Design Criteria

The Tembungo SALM has been designed to moor permanently a 94,000-DWT (85 000-Mg) vessel in the 100-year design environment. This environment and other pertinent design criteria are presented in Table 1.

The governing parameters for the structural design of an SPM terminal are the prediction of the statistically most probable peak mooring force and, for hawser-type systems, the selection of the bow hawser. The breaking strength of the hawser assembly will dictate the required structural capacity of the entire mooring facility. Peak mooring forces for the Tembungo SALM facility were determined by means of an empirical technique developed over the past 15 years through a continuing series of model test programs conducted by Exxon Research and Engineering and Exxon Production Research Co. The procedures used have been discussed in the literature by Flory and Poranski[4] and Maddox.[5]

Based on the given environmental conditions, the following peak design forces were predicted.

Maximum bow hawser load, kip (kN)	840 (3736)
Maximum anchor leg (axial) load, kip (kN)	1,200 (5338)
Maximum anchor leg deflection (with vertical), degrees	37½

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Fig. 1—The Tembungo SALM.

TABLE 1—DESIGN CRITERIA FOR THE TEMBUNGO SALM

Water Depth, ft (m)	296 (90)
Tanker size, DWT (Mg)	94,000 (85 000)
Significant wave height, ft (m)	21.0 (6.4)
Maximum wave height, ft (m)	39.0 (11.9)
Maximum wind velocity, mile/hr (m/s)	65 (29.5)
Maximum current velocity (perpendicular to waves), knots (m/s)	2.0 (1.0)
Product transfer piping, in. (mm)	10 (254)
Maximum operating pressure, psig (MPa)	200 (1.38)
Maximum surge pressure, psig (MPa)	400 (2.76)

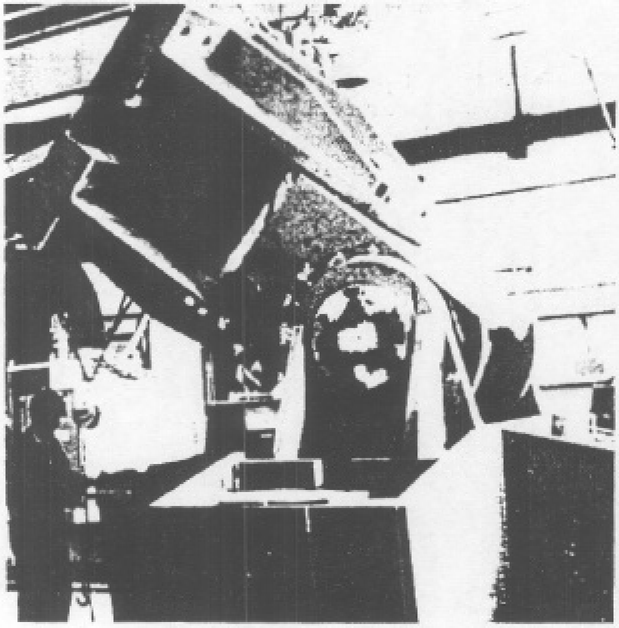

Fig. 2—Base universal joint.

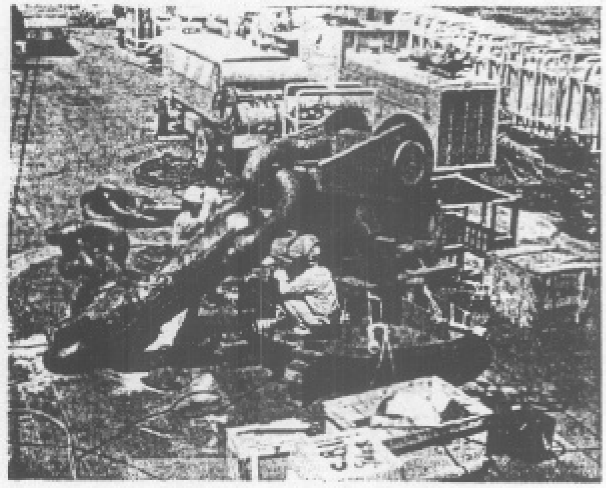

Fig. 3—Riser universal joint.

System Component Description[6,7]

The SALM mooring buoy is anchored through a single pretensioned anchor leg to a gravity-type mooring base at the seafloor (Fig. 1). The system is designed to remain constantly in tension during all operational and maximum storm conditions. The entire system was designed to be installed in three operations: set and ballast the base, attach the riser, attach the buoy. This procedure allowed the use of a small and inexpensive offshore construction spread. To minimize diver time and underwater work, the universal joint attachments between riser and base (Fig. 2) and buoy and riser (Fig. 3) were designed to be latched (or unlatched) hydraulically from the surface. Basic characteristics of the major SALM components are given in Table 2.

Operational Experience

The Tembungo field has produced continuously since Oct. 1974 at quarterly average rates varying from 2,000 to 16,000 BOPD (318 to 2500 m^3/d). For this 7-year period, the average overall operational efficiency—i.e., total days minus total downtime days divided by total days—has been 95%. Operational efficiency is described in the following and is shown graphically in Fig. 7 and tabulated in Table 3.

1974. [Last quarter of 1974 (operation started Oct. 14).] Eighteen days' total system downtime: 1 day for tanker change-outs (two tankers), 4 days for maintenance, and 13 days waiting for tankers to arrive (77% efficiency).

1975. Twenty-six days' total system downtime: 2 days for tanker change-outs (four tankers), 15 days for maintenance, 4 days waiting on tankers to arrive, and 5 days with tanker standing by because of rough seas (92.8% efficiency).

TABLE 2—BASIC CHARACTERISTICS OF MAJOR SALM COMPONENTS

Mooring Buoy (Fig. 4)	22 ft (6.7 m) diameter × 36 ft (11 m) high; internally divided into eight watertight chambers.
Riser shaft (Fig. 5)	8.5 ft (2.6 m) diameter × 185 ft (56 m) long.
Mooring base (Fig. 6)	Gravity-type, self-floating design; in-place weight 4,600 kip (20 400 kN).
Anchor leg assembly (Fig. 3)	6-in. (152-mm) grade oil rig quality stud-link chain including permanently lubricated underwater ball bearing swivel and universal joint.
Loading hose system	10-in. (254-mm) hose string made up of four specially reinforced submarine hoses (from hose arm to Surfaces 1, 2, 3, and 4), two surface floating hoses (Surfaces 5 and 6), and one tanker rail hose. All hoses are 35 ft (11 m) long.
Mooring hawsers	Two nylon hawsers 15 in. (370 mm) circumference × 150 ft (46 m) long with 3-in. (76-mm) diameter chafing chain at buoy and tanker ends.
Pipeline end manifold (PLEM)	Gravity-type connected to SALM riser by two hoses, 10 in. (254 mm) ID × 35 ft (11 m) long, in series.

1976. Forty-five days' total system downtime: 1 day for tanker change-outs (four tankers), 4 days for maintenance, 20 days waiting on weather (WOW) to do maintenance, and 20 days waiting on tankers of arrive (87.7% efficiency).

1977. Thirty-two days' total system downtime: 6 days for tanker change-outs (13 tankers), 8 days for maintenance, and 18 days WOW or waiting on equipment to do maintenance (91.2% efficiency).

1978. Five days' total system downtime: 4 days for tanker change-outs (12 tankers) and 1 day for maintenance (98.6% efficiency).

1979. Fourteen days' total system downtime: 4 days for tanker change-outs (11 tankers), 6 days for maintenance, and 4 days WOW for maintenance (96.2% efficiency).

1980. Nineteen days' total downtime: 2 days for tanker change-out (8 tankers) and 17 days for maintenance (94.8% efficiency).

1981. Two days' total system downtime: 1½ days for tanker change-outs (6 tankers) and ½ day for maintenance (99.5% efficiency).

The influence of weather on operating efficiency primarily affected maintenance activities; 47 days were lost or about 29% of total days down since 1974.

Total downtime for Oct. 14, 1974, through Oct. 18, 1981, was 161 days, which included 37 days of waiting for the tanker to arrive. Actual overall efficiency (discounting early logistics problems) is then 95%.

Inspection and Maintenance

1975. The first annual maintenance and inspection was conducted April 14–24. Maintenance consisted of changing out the submarine and floating hoses and buoyancy tanks. Two underbuoy hoses and all but one of the floating hoses were retained for future use.

No scour was evident around mooring base and PLEM; the universal joints and the chain swivel were in good condition; the fluid swivel showed no leaks; and the protective coating system on the swivel and hose arm was in good condition.

1976. The annual survey was conducted June 28–July 4. Twenty days WOW to do maintenance was incurred waiting to reconnect the submarine hoses, which had been removed to conduct a fluid swivel rotational torque test (Fig. 8). The test showed that hose kinking was not caused by swivel torque but by the excessive length of the hose string. The tankers were modified later in the year to allow bow loading in lieu of mid-ship loading, which had been employed since start-up.

Maintenance consisted of installing a new loading hose string, replacing mooring hawser assemblies, and sandblasting and painting the mooring buoy above the waterline. Additionally, the navigation lantern and batteries were replaced. A "Y" piece was installed on the hose arm to facilitate future hose replacements by allowing the old hose to be used as support while installing the new hose.

Inspection revealed the SALM to be generally in good condition, although the anodes had disintegrated more rapidly than anticipated. Steel construction debris left on the bottom and uncoated ballast bars in the hose arm counterweight were suspected of contributing to the rapid anode consumption.

1977. The SALM was shut in for 23 days for annual inspection and maintenance. During this time 9½ days were lost WOW and 6 days were lost from breakdowns on the maintenance vessel. Much of the weather and equipment downtime could have been avoided by better planning and the establishment of definitive maintenance procedures. The major task was the replacement of 42 cathodic protection anodes. Additionally, the buoy was sandblasted and coated above the waterline, and navigation lantern and battery pack were replaced. The loading hoses were replaced during this shutdown. Inspection of the U-joints, anchor chain, and chain swivel was not performed because of bad weather and excessive downtime replacing anodes.

Three days were lost during a shutdown in February in an attempt to replace the Surface 5 floating hose, which was chafing against the tanker's bulbous bow. Replacement was prevented because of bad weather. A total of 6 shut-down days were spent during tanker turnarounds in 1977.

1978. The annual inspection program was carried out April 20–24, during which time the SALM was inspected by divers using an underwater video camera. The Cam-Lok clamps, which connect the base hoses at PLEM and SALM riser piping, appeared to be deteriorated as a result of cathodic action. Bracelet anodes were installed, and one of the two clamps was replaced in 1980.

1979. The annual SALM inspection and maintenance program was conducted August 13–20. As a result of careful planning, production was shut in for only 13 hours while a new submarine hose string was connected.

TABLE 3—OPERATIONAL EFFICIENCY, DOWNTIME SUMMARY (days)

	1974	1975	1976	1977	1978	1979	1980	1981	Total by Item
Tanker change-outs	1	2	1	6	4	4	2	1.5	21.5
Maintenance activities	4	15	4	8	1	6	12	0.5	50.5
WOW to perform maintenance	—	—	20	18	—	4	5	—	47
WOW to moor or load	—	5	—	—	—	—	—	—	5
Waiting on tankers	13	4	20	0	—	—	—	—	37
Total (D/yr)	18	26	45	32	5	14	19	2.0	161

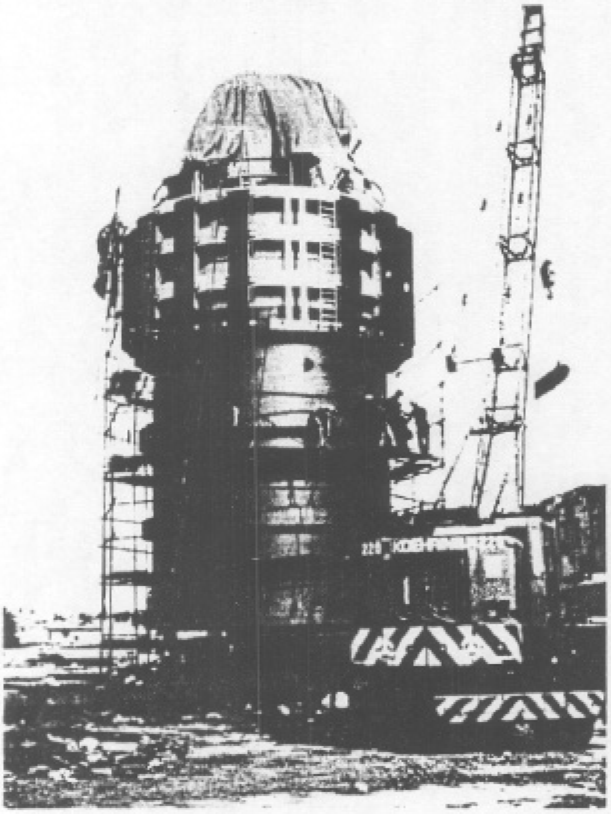

Fig. 4—Mooring buoy.

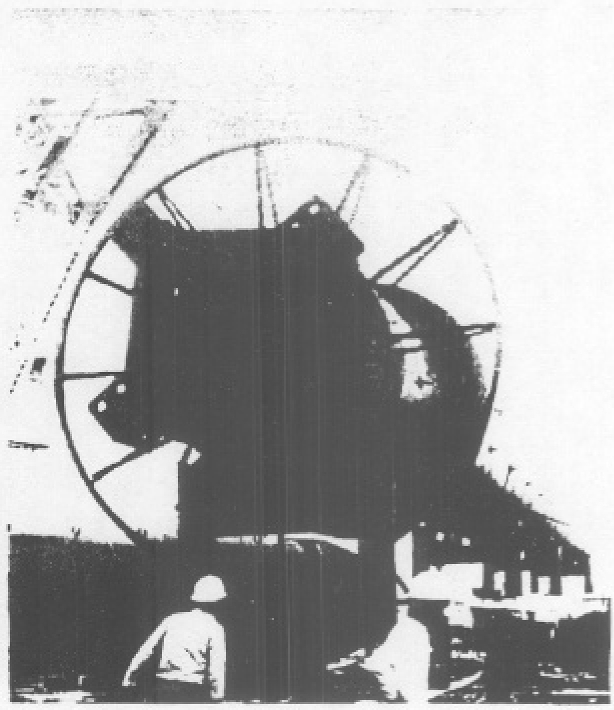

Fig. 5—Riser shaft.

Except for that time, the tanker was loading continuously during the entire inspection and maintenance program.

The hose inspection showed that liners and covers were in good condition. There was no evidence of scouring around mooring base or PLEM. Bracelet anodes at ends of PLEM-SALM hose were approximately 30 to 50% consumed. The universal joints and all other components were in good condition.[8]

1980. The annual inspection was conducted March 25–April 6, during which time the usual visual inspections were conducted, measurements were taken on the fluid swivel and chain assembly, and the 10-in. (25.4-cm) ball valve on the hose arm was replaced.

The most significant operation planned for this period was the replacement of the base hoses. While there had been no evidence of malfunction of these hoses after 5½ years' continuous operation, they were covered with a layer of marine growth, and replacement was done as a precautionary measure.

The work was done by a two-man saturation diving system working from a 150-ft (46-m) barge with a four-point mooring system. The replacement operation went very smoothly, and bracelet anodes were installed on the spool pieces between riser, hoses, and PLEM.

Later inspection showed both the original hoses and the Cam-Lok connections to be in good condition. Twelve days' downtime was required for this work; note, however, that during 70% of this period there were 6- to 7-ft (1.8- to 2.1-m) seas and 20- to 25-knot (10- to 12.5-m/s) winds.

On May 11, during a routine inspection dive, divers noticed that the gap between the two moving parts of the chain swivel had opened up considerably. The gap was measured to be 2⅞ in. (7.3 cm), compared with the original as-built gap of ⅛ in (0.3 cm). At this time the decision was made to install a spare chain swivel located at the warehouse in Kota Kinabalu. (Later, detailed investigation by the manufacturer revealed that swivel failure was due to failure of the oil seal between the shank and the barrel. Loss of lubricant and subsequent deterioration of the bearing in seawater caused bearing failure and total lock-up of the swivel. Since then a new seal arrangement has been designed consisting of a Turcite element energized by a Buna-N insert, plus a guide spacer to prevent "cocking" of the shaft during shipping and handling.)

Because the only support vessel available at the time was a 130-ft (40-m) supply boat with a four-point mooring system, it was necessary to wait for calm weather. By May 27 the gap was 4⅞ in. (12.4 cm). During this period, detailed preparatory work was carried out, including fabrication and installation of a support frame for the upper universal joint and a support cradle for the main shackle pin.

The vessel was anchored, and ballasting of the buoy began on June 1. After the chain assembly was slack, a 15-ton (13.6-Mg) hydraulic jack was used to remove the pin from the shackle connecting the chain assembly and universal joint. The buoy then was deballasted, the anchor chain assembly winched over the stern roller and onto the deck of the supply boat, and the buoy secured to the stern of the vessel. The chain swivel and connecting shackles were replaced and lowered into the water, and the buoy was reballasted. The four-point mooring system then was manipulated to position the shackle precisely

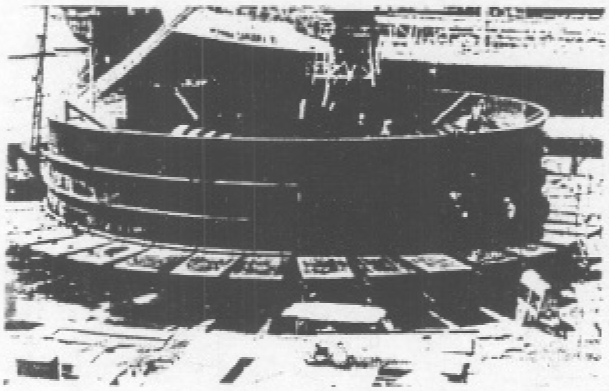

Fig. 6—Mooring base structure.

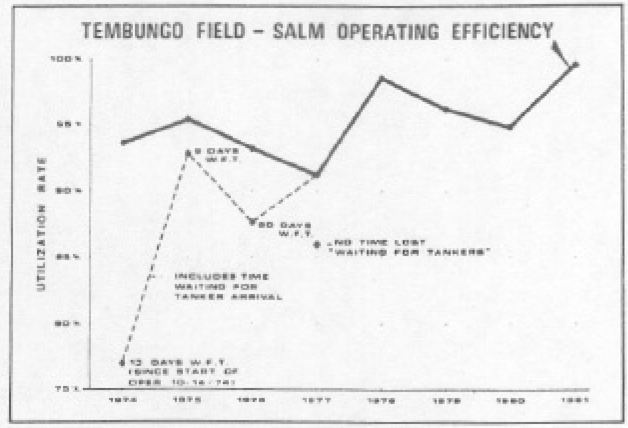

Fig. 7—Operating efficiency plot.

over the universal joint, and the pin was installed with the hydraulic jack and preinstalled pin cradle. Total downtime amounted to only 69 hours from shutdown of production to restart of production through the SALM, thus illustrating the value of thorough preparation (total preparatory dive was 9.5 hours vs. 8.9 hours diving during the actual replacement operation).

1981. The annual inspection was divided into two phases, with the first phase to cover the shallow components (from the hose arm up to the buoy) and the second phase covering the deeper components (from the top universal joint down to base).

Phase 1 was conducted during April 8–23, and except for the U-joint thrust washer the system was in good order. On April 14, during Phase 1, the routine inspection of the upper universal joint revealed that one washer had disintegrated. Several pieces of the broken thrust washer were recovered at the bottom of the U-joint housing. (Later, investigation revealed that failure occurred because of dezincification of the self-lubricating bronze thrust washer (ASTM B-22, Alloy E). Use of this alloy was discontinued by the fabricator several years ago in favor of a nickel aluminum bronze (ASTM B148, Alloy 955).

After discussions with local maintenance personnel it was decided to manufacture a mild steel washer on location. The washer was made in two halves from ¾-in. (1.9-cm) plate. The tanker was unmoored, the buoy ballasted down, and the two halves of the washer fitted in and wet-welded. Total production downtime amounted to 13 hours.

As of Oct. 1981 no swivel torque test had been carried out. Careful monitoring by divers and tanker crew gave no indication of any torque buildup, and the fluid swivel hose arm was moving relative to the tanker. No major immediate operational problems are foreseen, and regular monitoring will continue.

Phase 2 of the annual inspection was conducted in Aug. 1981, and all the deep components were found to be in good condition.

Early Operation Problems and Solutions

Initially there were certain operational problems that resulted in some system/production downtime. These initial operating problems were twofold:

1. The tanker had a tendency to ride up on the buoy in calm weather, causing kinking of the cargo hose directly off the hose arm.

2. The chafing chain at the tanker fairlead experienced accelerated wear.

The tankers *Esso Chile* and *Esso Cristobal*, which were used for most of the operating period covered by this paper, were unable to run their engines astern for extended periods without overheating their condensers, which made it difficult for them to maintain the necessary hose tension in calm weather.

Remedial actions considered included: (1) rotation of the hose by a workboat, (2) periodic reversal of tanker engines to tension hawser and hose string, (3) provision of tug boat to keep tension on the stern of the tanker, (4) installation of stern thrusters, (5) installation of 24-in. (610-cm) surplus marine hoses over 10-in. (25-cm) Cargo Hoses 1 and 2 to increase hose rigidity, (6) installation of a backstop on the hose arm to limit vertical excursion, (7) modification of the tankers to accept bow loading, thereby reducing the length of hose in the water, and (8) modification of the tankers to run continuously astern.

After discarding all other solutions as impractical or too expensive, and after consultation with the manufacturers of the ship's turbines, a simple, inexpensive modification was effected that allowed low speed (10 to 24 rpm) astern power to be maintained over an extended period. This modification featured installation of a 5-in. (13-cm) line from the desuperheated (saturated) steamline, which powers the cargo pumps to the steam inlet on the low pressure astern turbine.

The operating philosophy for engine reverse running was to run continuously at 10 rpm whenever windspeeds fell below 10 to 15 mile/hr (4 to 7 m/s). For the 50,000-DWT (45 000-Mg) class tankers, *Esso Chile* and *Esso Cristobal*, this procedure resulted in incremental fuel (diesel) consumption of 2 long tons (2032 kg) per full day of continuous astern running.

Additionally, the tankers were modified to allow the cargo hose to come over the forecastle rail at a point about 20 ft (6 m) abaft the stem. This modification reduced hose maintenance by helping prevent kinking of the long hose string and by eliminating chafing against the ship's bow. The use of astern power substantially eliminated operating problems at the Tembungo SALM,

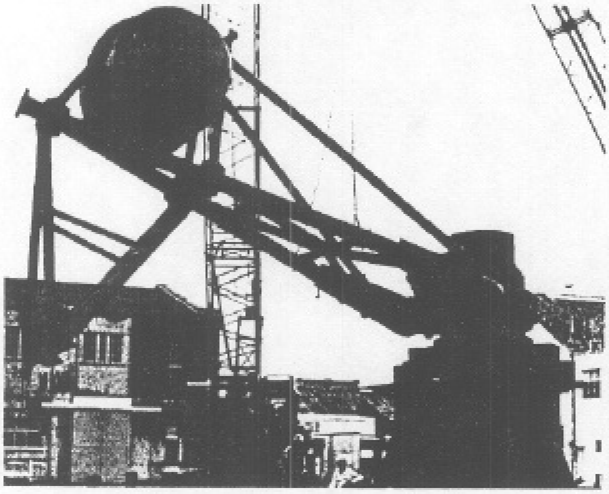

Fig. 8—Fluid swivel.

TABLE 4—TEMBUNGO SALM TYPICAL COSTS (1982 U.S. dollars)

Complete SALM hardware and hose system for bow loading	5,500,000
Transportation, installation, and commissioning	2,000,000
Total cost (without pipeline)	7,500,000
Modifications to allow continuous slow astern power	20,000
Bow loading modification	25,000
Incremental diesel fuel cost at $1.00/gal assuming 80% astern running annually	270,000/yr
Maintenance vessel and crew charged to SALM	600,000/yr
SALM maintenance costs	250,000/yr
Replacement costs of hoses, hawsers, and chafing chain	100,000/yr

as evidenced by the average 7-year terminal efficiency of 95% and the last 4 years of 97.2%.

1978	1979	1980	1981
98.6%	96.2%	94.8%	99.4%

The problem of excessive chafing chain wear was greatly reduced by the application of astern power and frequent lubrication of the chain where it enters the tanker bow chock. The average frequency of chain replacement has been approximately every 3 to 4 months and is generally coincident with tanker change-outs.

Costs

Of particular interest to potential operators of offshore loading systems are the overall costs involved. For the Tembungo SALM in 1982 dollars, typical costs are given in Table 4.

Conclusions

The Tembungo SALM has proved a mechanically sound system that allowed bringing a small field onto production earlier and cheaper than would have been possible by other means. The design criteria of 95% operational efficiency has been met, as indicated by the operating history described in this paper.

Pertinent conclusions offered by this history are as follows.

1. The importance of prudent tanker selection to optimize performance and minimize modifications.
2. The importance of planning maintenance and inspection activities and of developing practical offshore procedures for the replacement of hoses and hawsers.[9]
3. The necessity of having capability to apply slow astern power for extended periods.
4. The inherent low maintenance features of the mooring system.

It is important to re-emphasize that only two major components of the Tembungo SALM have required maintenance of any significance since start-up in 1974. This low requirement for maintenance on SALM components may be attributed to the inherent advantages of the SALM system and to novel design features that eliminate the necessity for periodic lubrication of the fluid swivel, chain swivel, and universal joints. With a properly modified tanker and careful attention to planning and training functions, a competently designed hawser-type SALM mooring system can provide an efficient, low-cost offshore storage/loading facility.

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SI Metric Conversion Factors

ft	× 3.048*	E−01	= m
mile	× 1.609 344*	E+00	= km
naut mile	× 1.852*	E+00	= km

*Conversion factor is exact.

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