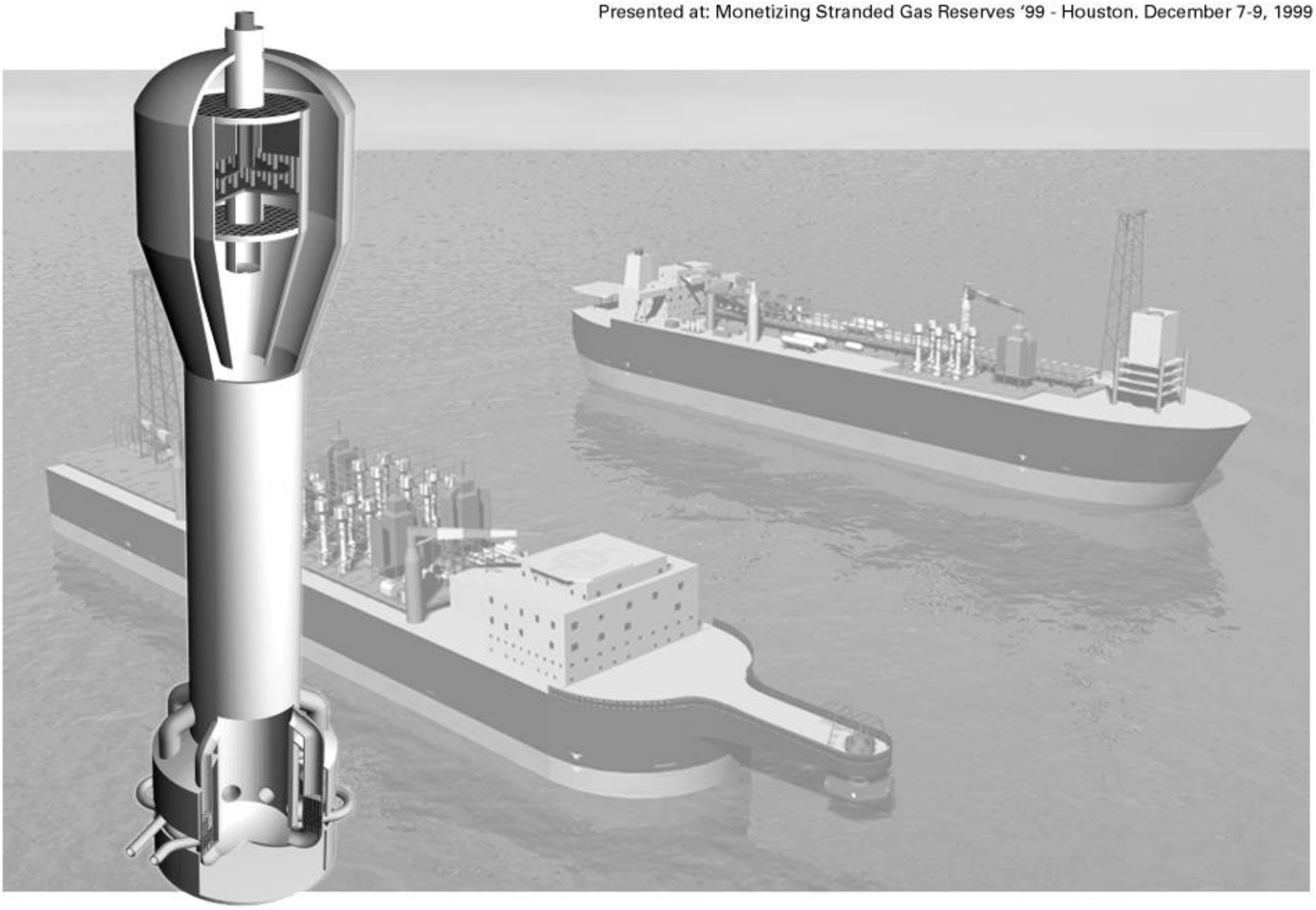
THERMOACOUSTIC REFRIGERATION

A STIRRING CONCEPT FOR OFFSHORE ASSOCIATED GAS LIQUEFACTION

Presented at: Monetizing Stranded Gas Reserves '99 - Houston. December 7-9, 1999



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THERMOACOUSTIC REFRIGERATION - A STIRRING CONCEPT FOR OFFSHORE ASSOCIATED GAS LIQUEFACTION

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Abstract

With the TADOPTR technology it will be possible to economically convert associated gas produced on floating offshore oil production installations into LNG. A concept is presented with which this could be achieved once the TADOPTR technology has been further scaled-up, i.e. within approx. 4 years.

The base case concept assumes an Oil-FPSO on which the associated gas is pre-treated for liquefaction, after which the treated gas is transferred to a separate LNG-FPSO permanently moored nearby. The gas is liquefied on this FPSO and stored until it is off-loaded to a shuttle carrier.

The gas treating and liquefaction processes are described, and an economic evaluation of the concept has been produced. The results of the economic evaluation are highly attractive. The “landed” cost (i.e. including a shipment range of 1,600 nautical miles) is only 2.29 US$/MMBtu if the associated gas feed is at zero cost. In case the cost of feed gas is e.g. 0.5 US$/MMBtu, the “landed” cost will be 2.80 US$/MMBtu, which is still competitive in international LNG trading.

Another, even more attractive scenario could be developed in the further future, in which both FPSO’s are integrated in one vessel. For such a scenario, the typical “landed” cost would be as low as 1.09 US$/MMBtu (zero cost feed gas), to 1.59 US$/MMBtu (with feed gas at cost of 0.5 US$/MMBtu).

1. TADOPTR - The Key Technology

TADOPTR stands for: Thermoacoustically Driven Orifice Pulse Tube Refrigeration. This technology uses the energy stored in acoustic waves to liquefy gases. With this technology it is in principle possible to achieve cryogenic temperatures.
The TADOPTR technology is essentially a cooling machine based on a modified Stirling refrigeration cycle, except that the working gas that achieves the cooling is not displaced and (de)compressed by means of pistons, but by means of acoustic wave power. The working gas is Helium.
An outline of the TADOPTR is shown in Figure 1.

Figure 1: TADOPTR Outline. The Thermoacoustic Engine is at the top, the Thermoacoustic Refrigerator with the gas heat exchangers is at the bottom.

The technology is very safe, simple, reliable, cost effective, and it has no moving parts at all. These factors mean that the technology has a strong advantage over other gas conversion technologies, especially for offshore applications or in remote locations.

The technology has been under development with Los Alamos National Laboratory (LANL) and the National Institute of Standards and Technology (NIST) in Boulder, with strong support from the USDOE Federal Energy Technology Center.

The TAD is a so-called heat engine, in which thermal energy is converted into mechanical work, in the form of an oscillating pressure wave. The acoustic power in the TADOPTR is generated by imposing a steep temperature gradient across a specially designed heat exchanger at the other side of the apparatus called the stack, which causes the working gas to vibrate at the TAD side, thus causing a standing wave oscillation in the apparatus. The acoustic energy is transferred from the TAD to the OPTR via the so-called resonator. The length of the resonator determines the oscillation frequency of the standing wave. The TADOPTR design presently under development uses a frequency of approx. 40 Hz. At the OPTR, which is essentially a heat pump, the acoustic energy is converted into cooling power. See figure 2.

Figure 2: Details of the Thermoacoustic Engine and Refrigerator.

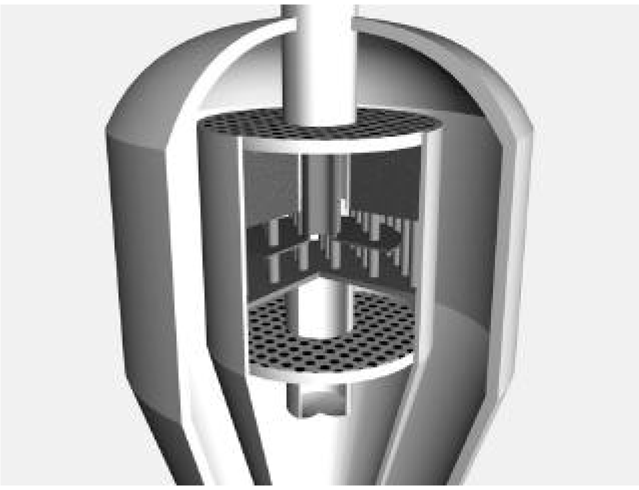


Fig. 2a

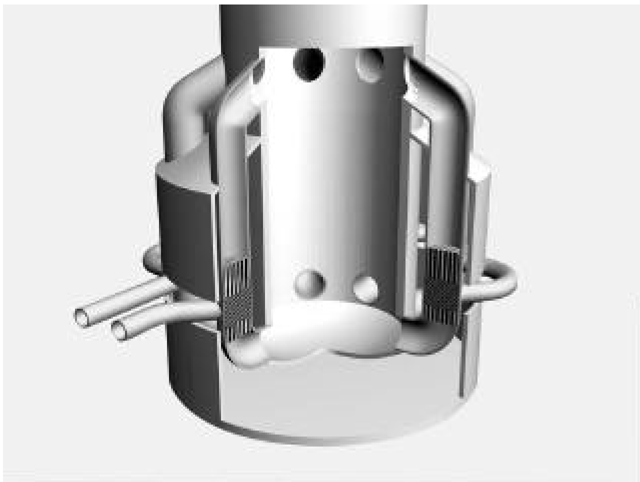


Fig. 2b

The Engine is shown in fig. 2a. The steep temperature gradient across the hot heat exchanger and the ambient heat exchanger causes the Helium to oscillate up and down. During this process heat is exchanged with the stack in between the heat exchangers in a way that thermoacoustic work is produced. This work is then transferred to the Refrigerator at the other end of the resonance tube, where the reverse process takes place, i.e. thermoacoustic work is converted to cooling power. Fig. 2b shows the refrigerator and the flow of the liquefied gas through the heat exchangers.

Naturally, the overall efficiency is bound by the Carnot efficiencies of the heat engine and heat pump, like in any other thermodynamic process. Apart from these fundamental limitations, the second-order efficiencies of the TADOPTR are only dependent on engineering choices in order to arrive at a low-cost and practical design of the apparatus.

The TADOPTR has no moving parts whatsoever. The TADOPTR only needs fuel gas for heating the TAD side of the apparatus, and a suitable cooling medium (e.g. water) to serve as a heat sink for the TAD and for the cooling machine (the OPTR).

The TADOPTR technology needs further development until it is suitable for relatively large-scale applications (i.e. cooling capacities of several hundreds of Kilowatts or more). The status of the development is such however, that there is a large degree of confidence that further scale-up and efficiency improvement will be feasible within a reasonable time scale, e.g. 3-4 years. For relatively small units, e.g. up to approx. 150 - 300 Kilowatts, first commercial application could be within 2-3 years. The underlying thermodynamic and physical phenomena are well enough understood to enable prediction of large unit performances.

The main challenges during the further development will be in the engineering and product development areas, with the red-hot heat exchanger in the TAD being the most critical item.

The expected efficiency of the next prototype TADOPTR, scheduled for testing within a few months, and which is a 500 USgpd unit (based on methane liquefaction), will be to liquefy 70%/burn 30%. This is a leap step improvement compared with the performance of the 140 USgpd unit with a fuel efficiency of 40% which was successfully tested during 1998, indicating that there is room for further improvement.
The aim of the development program is to further improve the fuel efficiency to approx. 85%/15%, and to scale up the apparatus to a cooling capacity suitable for plant sizes of 1 - 60 MMscfd.

2. A totally new Offshore Liquefaction Concept

In addition to other market applications, this exciting technology is perfectly suitable for offshore liquefaction of associated gas. Offshore LNG production is under consideration by several industrial groups, but most of them concentrate on stand-alone large gas field developments, with LNG train capacities of at least 1.5 MTPA.
The TADOPTR technology is not intended to be used for large-scale base-load plants. It is probably not the right technology for that scale, at least not for the foreseeable future.
However, the size of many offshore oil field developments result in quantities of associated gas that fit well within the capacity of a TADOPTR-based liquefaction plant.

For the purpose of this paper, a typical offshore development scenario has been selected. This case discusses an offshore oil field, in a relatively benign environment, such as e.g. offshore W-Africa, Brazil, SE-Asia, Australia, or the Gulf of Mexico.

A conservative approach has been adopted, by assuming separate vessels for the oil production and storage, and for the gas liquefaction and LNG storage. This has been chosen because offshore LNG production is not a well known area of expertise. Assuming that integration of oil production and LNG production can be done without having any offshore LNG production experience would be too optimistic. The concept is shown in Figure 3 below.

Figure 3: Artist Impression of Offshore Associated Gas Liquefaction Concept

A typical FPSO-based offshore oil field development has been selected for the scenario evaluation. The associated gas feed conditions for the gas treating and liquefaction plant, and the required product specifications for the LNG are shown in Table 1 below.

Table 1: Feed Properties and Product Specifications

Feed Property	**Quantity**
Feed pressure	50 bar ga
Feed temperature	50 deg.C
Feed rate	53.5 MMscfd
Net Heating Value	1357 Btu/scf
Feed Composition	See below
- Water	Saturated at feed P, T
- Nitrogen	Negligible
- Carbon dioxide	1.6
- Hydrogen sulfide	50 ppm
- Methane	74.6
- Ethane	8.3
- Propane	4.6
- I-butane	1.5
- N-butane	1.8
- I-pentane	1.2
- N-pentane	1.3
- Hexane	0.9
- Heptane +	2.5
Product Specification	
Product pressure	0
Product temperature	-160
Product Specification	See below
- Water	1 ppm
- Hydrogen sulfide	3.5 ppm
- Carbon dioxide	50 ppm
- Pentane +	0.1 mol-%

A simplified Process Flow Scheme (see figure 4 below) shows how the process works. The gas to be liquefied will be pre-treated on the oil FPSO to LNG quality specification, typically at first stage separator pressure level. Gas compression will thus not be required. The gas is purified by removing CO2, H2S (if present), water, and mercury if present.

First, CO2 and H2S are removed in a 2-stage MDEA absorber. The absorber is split in two stages to limit its height, thus limiting its performance degradation due to ship motions. The rich MDEA is regenerated in a standard AGR (Acid Gas Removal) Unit, which has been applied offshore already, albeit on a fixed installation. Stork also made this design.

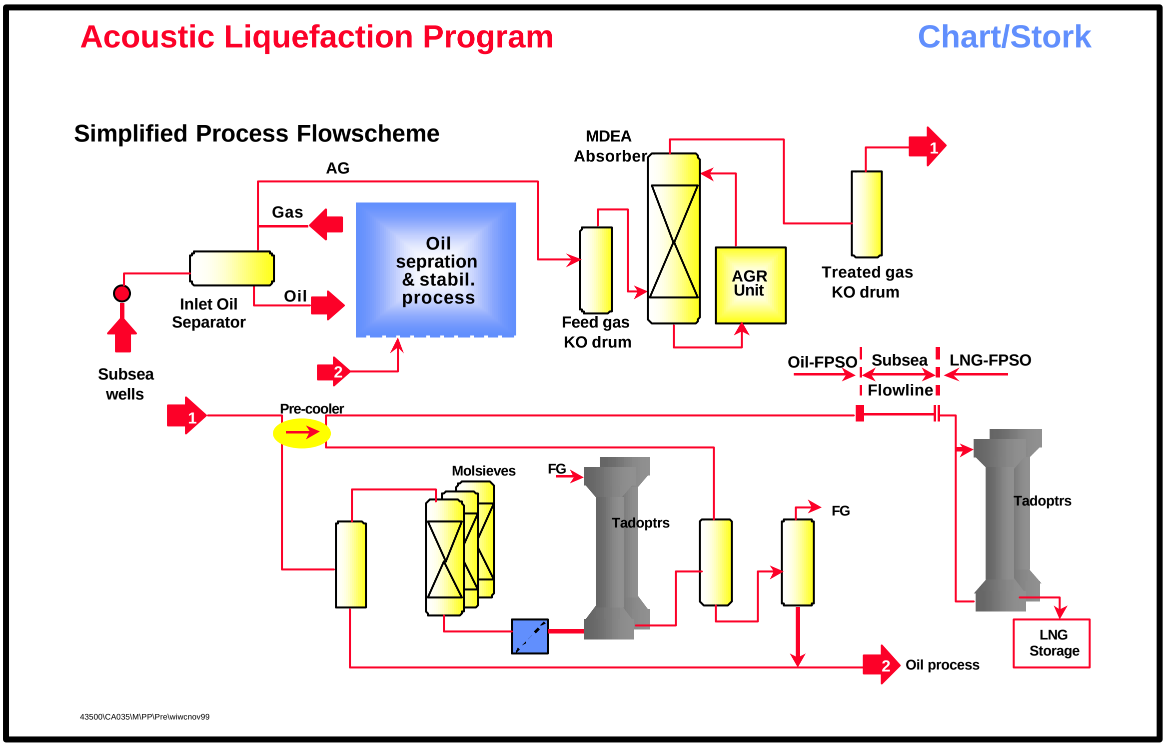
The CO2 and H2S-rich off-gas is burned in an incinerator, assisted by a minimal amount of fuel gas to support the combustion.

The gas leaving the AGR absorber is water saturated, of which the bulk is removed by simple gas-liquid separation at a temperature just above the gas hydrate temperature. Thereafter the gas is further dehydrated in a molecular sieve unit to LNG dewpoint specification.

Finally the gas is cooled to -30 deg.C to condense the heavy hydrocarbons (HC). Because of the low water dewpoint, hydrate inhibitor injection is not required. The separated HC condensate is returned to the oil separation plant, where most of the heavier components will dissolve in the crude oil. A small fraction will re-evaporate (less than 5 %) causing the feed stream to be slightly increased and slightly enriched in C3 and C4-concentration. For the cooling process TADOPTR technology can also be applied, which has been assumed for this study. This could however be done equally well using any other chilling unit.

The pre-treated gas is then ready for transport to the LNG-FPSO, where it will be liquefied. The purified gas leaves the Oil-FPSO through the turret swivel in the bow of the Oil-FPSO. A gas riser takes it down to a short flowline at the sea bottom, from where gas is routed to the LNG-FPSO. There a gas riser takes it up to the feed gas swivel in the external turret of the LNG-FPSO. The estimated flowline length will be approx. 1.5 - 2 kilometers, to avoid interference during off-loading and weathervaning. The flowline design pressure for the scenario considered is approx. 50 bar ga. The flowline can be a normal grade carbon steel line pipe. The flowline diameter is 8 inch; insulation is not required.

Figure 4: Simplified Process Flow Scheme of Gas Treating and Liquefaction System



Once on the LNG-FPSO, the gas undergoes neither further treatment nor separation of liquids. The entire gas stream is liquefied in the TADOPTRS. The TADOPTRS are arranged as parallel units, with four (4) TADOPTRS in a single standard module. In total four (4) modules are required. Each TADOPTR has a number of serial heat exchangers through which the gas flows. As the gas is successively cooled in these heat exchangers, the pressure is also gradually reduced until atmospheric pressure is achieved in the final cooling stage. The LNG is finally stored in the LNG storage tanks. The overall fuel efficiency of the gas treating and liquefaction process is 82 % on a combustion energy basis. The Net Heating Value of the LNG product is 1064 Btu/scf. The fuel efficiency is defined as the ratio: Btu's LNG product **:** (Btu's AG feed **-** Btu's to Oil process).

The LNG tanks are of the modular SPB type, as supplied by IHI, or equivalent. The storage capacity is 50,000 m^3. This tank arrangement results in a totally free deck space for installation of the TADOPTR modules. They can be designed to fit in any conventional crude carrier, if desired. This storage volume allows an off-loading frequency of approx. 1 month. This tank design also allows integration of oil as well as LNG storage on a single Oil-LNG FPSO, which could become a future development.

The heating system for the TADOPTR modules is based on direct heating using a conventional type furnace with recuperator, which is feasible, but which may ultimately prove to be not the most practical solution. Other methods of heating are under study, such as using a closed-loop Helium heating system, and the use of heat pipes. The heating requirement for the TADOPTRS is rather high, due to the nature of the technology, which uses heat to generate mechanical work, instead of pressure, as is the case in conventional refrigeration. The total heating duty for liquefaction on the LNG-FPSO is 85 MW.

The cooling water supply to the TADOPTRS is via an intermediate closed-loop cooling water circuit, which in turn is cooled by seawater. The cooling could eventually also be done by direct seawater cooling, which is a trade-off between TADOPTR costs and cooling system costs. The cooling requirement is also high, for the same reason as the heating requirement. The cooling duty on the LNG-FPSO is 72 MW.

The gas treating process is kept on the oil-producing FPSO, to allow maximum integration with the oil process and ship utilities. For example, the separated heavy hydrocarbons can be spiked back into the oil separation process, where most of it dissolves in the crude oil again. For the regeneration of the molecular sieves, recuperated heat from the exhaust of the power plant has been used. The same applies for the reboiler of the MDEA regeneration column. Hot oil has been selected as heating medium. Power for e.g. the MDEA solvent pumps is limited, and is obtained from the FPSO power plant. The cooling water requirement on the Oil-FPSO is 14 MW, and is therefore shared with that of the oil process. Since no gas compression is required for this process, its operation can be made very reliable. The system will be capable of operation under motion, as the only motion-sensitive pieces of equipment are the MDEA absorber and MDEA regenerator. Therefore the MDEA absorber has been split into two columns, to limit the number of stages between redistribution, and to limit the total height of the columns. The TADOPTRS are not sensitive to motions, like the molecular sieves.

The liquefaction process on the LNG-FPSO is extremely simple. It is basically a number of parallel-operated TADOPTRS, together with the heating system and the cooling water system. There is no need for storage or blow-down of flammable refrigerant. The amount of gaseous and liquefied natural gas above the deck is minimal: only feed and return piping and the TADOPTR heat exchanger tubes. There is no distillation process or other separation process involved. The amount of rotating equipment is limited to the use of pumps in the MDEA regeneration unit, and for utilities such as cooling water, hot oil, and seawater. There are neither gas compressors nor gas turbines in

this plant. The turndown capability is very good: the desired number of TADOPTRS can simply be taken out of operation, without effect on the overall processing efficiency.
Operation of the plant is also relatively simple, because of the absence of a condensing refrigerant. A TADOPTR can easily be switched off. The start-up will take more time, as the TADOPTRS need to be warmed up at the hot end, although this can be done rather quickly (within a few hours).
The hot and cold parts of the TADOPTRS are well separated from each other. Also the footprint is reasonably small, as is the topsides weight. The overall installed dry weight of the gas treating plant on the Oil-FPSO, complete with utilities etc. is approx. 1,900 metric tons. That of the LNG-FPSO topsides plant is approx. 4,500 metric tons.

These facts all together make this process very robust from an operational and safety point of view.

Because the TADOPTR technology is still under development, there are certain potential technology risks, which will have to be mitigated during the scale-up phases.
The technical risks can be divided in two areas, i.e. those of the TADOPTR development itself, and those associated with applying LNG liquefaction, and in particular with this technology, on board of offshore floating facilities.
For the TADOPTR technology development, the main issues to be addressed and demonstrated will be: noise production, vibration, fatigue, hot end design (heat exchanger, material stresses), large-scale performance, and reliability. These issues will all be addressed during the next development phase.
For the risks associated with offshore LNG production, the same issues need to be addressed as for conventional offshore LNG processing. These issues have been addressed already by many others in various safety assessment studies. Of course the magnitude of certain risks will be totally different for the TADOPTR liquefaction plant than is the case for a conventional plant. For example:

- the explosion risk and magnitude of refrigerant operation under pressure and storage
- plant warm-up after shutdown and consequential overpressure protection and depressurizing requirements
- dispersion of heavy hydrocarbons from leakage
- presence of furnaces instead of internal combustion engines
- personnel risk during maintenance
- differences in logistics transport frequencies, and
- operational risks
    - such as cold-box performance or heat exchanger plugging,
    - performance of the MDEA absorber,
    - motion sensitivity of the different processes, etc.

Again, in due time these risks will have to be adequately addressed.
However, the overall impression is that an LNG liquefaction process using the TADOPTR technology is substantially safer than conventional technology.

3. Scenario Economic Evaluation

For the above scenario an economic evaluation has been performed. The results are summarized in Tables 2 and 3.
Two cases have been considered: one with separate vessels for Oil and LNG production, which is on the shorter term the more probable scenario, and one where the Oil and LNG production are

integrated on one FPSO. The latter is of course more attractive from an operational, logistics and economic point of view. The disadvantage is that there is no experience yet at all with offshore LNG, which may cause an integrated concept to be regarded as too risky. Therefore the integrated scenario is only shown for reference, and to show a potential future development.

Table 2: Total Installed Cost (Capex) – million US$

	Vessel	Separate vessels	Integrated vessel
Gas treating	Oil FPSO	32	32
Gas flowline and risers	Subsea	8	n.a.
Gas liquefaction	LNG FPSO	70	70
LNG tanks Hull and LNG tanks	Oil FPSO LNG FPSO	n.a. 90	40 n.a.
Mooring	LNG FPSO	15	n.a.
Off-loading	Oil FPSO LNG FPSO	n.a. 10	10 n.a.
Offshore installation/hook-up	Both	15	5
Total Capex		**240**	**157**

The Capex for the gas treating and liquefaction plant is based on detailed equipment and material bulk estimates, generated with an advanced cost estimating tool, which uses P&ID's and the layout as estimating basis, and which uses typical offshore parameters for material specifications, construction and installation.

Of course there is an amount of uncertainty in the Capex, mostly caused by the cost of the TADOPTR units, as these units are still under development. Nevertheless, a good effort has been made to do a detailed TADOPTR manufacturing cost estimate, based on a thermoacoustically checked pre-design, on materials used, on manufacturing methods and related typical costs of the future supplier of these units: Cryenco Inc., Denver, Co.

The Capex for the gas treating and liquefaction plant, as well as the related utilities, accounts for direct costs (installed), indirect costs, freight, engineering, overheads, fees, escalation (2 % per year), project management costs, and a 15 % contingency factor on the direct costs. Cost of taxes and permits, royalties and plant start-up are excluded. The estimate is based on a modular construction approach, with e.g. four (4) TADOPTRS in a single module, and with a number of identical parallel modules. This construction approach leads to significant cost savings, due to the high degree of standardization.

The total installed cost for the gas treating and liquefaction plant together amounts to 102 million US$.

A reputable Korean shipbuilder who is active in the FPSO and LNG shipping business has provisionally estimated the costs for the other elements of the concept. In a next development stage the concept needs to be further evaluated with respect to the following issues: integration of the LNG plant with the ship's systems, the off-loading needs to be addressed in more detail (this is a separate technology development that now nears the commercialization phase as well), safety studies, and a more detailed cost estimate of the LNG ship, off-loading and mooring systems.

Table 3: Plant Economic Evaluation Results

	Units	Separate vessels		Integrated vessel	
Evaluation Basis					
Associated gas feed	MMscfd	53.5		53.5	
Treated gas to LNG FPSO	MMscfd	41.4		41.4	
LNG production (design)	m^3/d (equiv. MMscfd)	1330 (34.6)		1330 (34.6)	
Uptime	%	95		95	
Utilization factor (= time avg./peak)	%	52		52	
Overall fuel efficiency	%, on Btu-basis	82		82	
Btu ratio (LNG product : gas feed)	----------	0.51		0.51	
Plant life	Years	20		20	
Gas-Oil ratio (GOR)	Scf/bbl	500		500	
Capex	**Million US$**	**240**		**157**	
Feed gas cost	US$/MMBtu	0.0	0.5	0.0	0.5
IRR (pre-tax)	%	15		15	
Transport distance	Nautical miles	1600		1600	
Location	----------	Benign, mild climate		Benign, mild climate	
Storage capacity LNG	m^3	50,000		50,000	
Evaluation Results					
Cost of production (discounted)	US$/MMBtu	1.57	2.08	0.37	0.87
Cost of transport	US$/MMBtu	0.72		0.72	
“Landed” cost	**US$/MMBtu**	**2.29**	**2.80**	**1.09**	**1.59**

For the economic evaluation it is important to note that in the selected scenario a significant portion of the associated gas is not liquefied to LNG product. This is due to the relatively rich gas quality, which contains a relatively high concentration in heavier-than-methane components. The methane concentration in the associated gas feed is only 74.6 mol-%. On a Btu-basis only 51 % of the gas ends up in the LNG product. About 38 % of the Btu’s is condensed as heavy hydrocarbons in the gas treating plant, and is routed back to the oil separation and stabilization process. This therefore results in a not insignificant extra oil production of approx. 47 m3/hr or 7,000 bpd initially (6 % of the oil production over the years), for which the economic benefits should be added to the balance of revenues and expenses of the LNG plant. For the extra oil revenues a price of 10 US$/bbl is assumed. The design oil production, including the condensed heavy hydrocarbons from the associated gas, is 114,000 bopd.

The overall economics are very favorable. The total “landed” cost of the LNG produced from associated gas at a distance of 1,600 nautical miles amounts to 2.29 US$/MMBtu. This can

compete with even the large-scale international LNG trading, which is quite surprising for such a small scale.
The Cost of production per barrel oil produced is only 0.51 US$.
For a desired return on investment of 15 % (pre-tax), the "landed" LNG cost per ton produced is 175 US$/ton, based on the total concept lifetime expenditures and revenues, including an annual Opex of 2.5 % of the Capex, and additional variable operating costs at 1 % of the Capex, for the corrected production ratio over the field life. When the cost of feed gas is not zero (or even negative), but is assumed to be at a cost of e.g. 0.5 US$/MMBtu (0.62 US$/Mscf), the "landed" LNG Cost of production would increase to 2.80 US$/MMBtu. Again, this wouldn't be a showstopper for this concept.

4. One Step Further

The information provided in this paper and the level of detail for the liquefaction plant are intended to demonstrate that this concept can be a very attractive one, operationally, from a safety point of view, reliability, performance efficiency, and last but not least from an economic point of view. This despite the fact that not all issues have been addressed in full detail, such as the design integration with the ship, off-loading, and mooring costs. They are probably accurate within 30 %, and therefore provide a sufficiently solid basis for this stage of the concept development. The most important matter is that it is demonstrated that the liquefaction process itself can be made very efficient and installed at a sufficiently low cost.

Although the integrated Oil-LNG FPSO seems to be too far reaching because it combines several new elements in it, such as offshore LNG production (never done yet), and a perceived higher safety risk due to the combination of two production processes that traditionally were never applied together, the economic attractiveness of such a concept is enormous. Imagine that the cost of small-scale associated LNG production could compete with today's world-scale LNG base-load plants: it is a real threat to some, but at the same time it's a challenge for others. It may mean a complete turnover of the future LNG manufacturing and trading business, leading to a more decentralized production, lower investment risks, less political risks, smaller scale transportation systems, a better distribution infrastructure, and thus a gradually growing spot market for LNG. It will lead to use in many other applications too.

Finally, the TADOPTR technology lends itself perfectly for modularization. Any number of TADOPTRS can be paralleled, using standardized equipment sizes. The manufacturing of the TADOPTRS and of the modules could be highly optimized for low cost and short delivery. This fabrication method minimizes field installation work.
In fact, it may well be the case that it is more attractive to manufacture units of relatively small cooling capacity rather than the biggest possible. The optimum size has not yet been determined, and will be a trade-off between the required different scale dimensions and production optimization requirements.

5. Typical Market Applications

Since the TADOPTR is a universal cooling machine, but with the unique capability to achieve cryogenic temperatures, the potential applications are numerous.

Particularly the use of the inflammable and environmentally-friendly Helium as a working fluid, and the total absence of moving parts in the apparatus, make this technology suitable for applications where low cost, reliability, safety, flexibility, and minimum maintenance are of crucial importance. The most significant application is probably natural gas liquefaction. For this application several other markets can be identified in addition to associated gas liquefaction, such as:

- Peak-shaving in local gas distribution
- LNG as vehicle fuel for fleet operators, instead of CNG (=Compressed Natural Gas)
- Coal-bed methane liquefaction
- Small-scale isolated (i.e. remote) gas wells without pipeline access
- Boil-off gas reliquefaction from LNG storage tanks and carriers
- Dewpointing of natural gas in gas treatment plants
- LNG production to serve as clean feedstock for small IPP's in remote areas.

One could also think of other applications, i.e. to liquefy other gases than natural gas. Consider for example an air separation unit for the production of oxygen or nitrogen, C2-C3 splitting in refineries or chemical plants, volatile organic compound recovery from storage facilities, CO2 recovery for re-use e.g. in greenhouses.

Due to the inherent simplicity of the technology, it can be deployed efficiently at much lower capacities than is the case now, especially for small-scale LNG production. In the future it will be possible to achieve cryogenic temperatures much easier. That alone will generate new market opportunities and new process developments throughout the industry.

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