

THE CRYOSTAR magazine

SPECIAL REPORT
reliquefaction
system EcoRel

Reliquefaction that's economical,
user-friendly and safe

The engineering design tools used

Successful liquefaction test



This issue of the CRYOSTAR Magazine is entirely dedicated to the first EcoRel on-board LNG re-liquefaction units produced by Cryostar.

You will learn about the technology involved, the tools, means and infrastructure which were implemented, the testing of the units and the position of Cryostar in the LNG ship market.

The project of delivering 14 such units within 24 months is one of the main challenges Cryostar has ever faced. It is an example of the values we advocate in our company, namely taking up challenges, being innovative, and being passionate about what we do. Our people, in all departments, have worked intensively on this project with great enthusiasm. It was not plain sailing, but overall we were very pleased with the achievements.

The production of the EcoRel units is also a step forward in Cryostar's core competencies. From a pure supplier of rotating machines, we have evolved into a supplier of process solutions around natural gas liquefaction and distribution and clean energy applications. To achieve this change we have hired process engineers, project managers, sales engineers, test engineers, and service engineers. Now we employ more than 400 highly qualified people who are all supportive of our strategy and our company objectives.

What will be Cryostar's next challenge? It won't be long before you'll be reading about it in one of our next issues!

Daniel MEYER
President



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EcoRel, how it works

Thanks to its low power consumption, the Cryostar EcoRel Boil Off Gas (BOG) re-liquefaction system has been selected to equip the largest ever built Q-Max series LNG carriers (14 vessels on order already).

The concept of EcoRel is to be economical but also user-friendly and safe for the environment.

It performs full re-liquefaction of the BOG. Cryostar has designed the process as well as the machines. This guarantees the best possible match between the process and the rotating equipment.

History of LNG carrier propulsion

Natural gas is transported over long distances in liquid form, at ambient atmospheric pressure, near its boiling point (-163°C) in insulated tanks onboard LNG carriers. Due to unavoidable heat inleak during the voyage, a portion of the cargo vaporizes, equivalent to about 3 % of the total volume over 20 days. In order to maintain the tank pressure close to atmospheric pressure the vapor generated by this vaporization must be removed from the tank.

Historically, so as not to waste it, the BOG was burned in boilers to produce steam for the ship's propulsion. Until very recently all LNG carriers relied on steam turbines for their propulsion and are the last vessels built with this type of propulsion. However, in recent times, the evolution of fuel costs, and the lack of crew with steam propulsion experience, has promoted innovation in the conservative LNG carrier world.

Two new propulsion systems are now being implemented in addition to steam turbine propulsion. Other propulsion systems, like gas turbine or 250 bar gas injection, are still under investigation.

One of the two new concepts was the Dual Fuel Diesel Electric (DFDE) system. It burns the BOG (at ~ 6 bar) in dual fuel diesel engines (gas or diesel oil). These engines drive generators to produce electricity for the electric motors driving the ship. Cryostar collaborated actively with shipbuilders in the development of the gas handling system for these vessels and has supplied the compressors for all delivered DFDE LNG carriers.

The other concept, subject of this article, completely splits cargo handling from the propulsion of the vessel. It maintains the cargo pressure and inventory by re-liquefying the BOG generated in the tanks and relies on cheaper heavy fuel oil (HFO) for the ship's propulsion using slow speed diesel engines.

Following an intensive 15-month testing process by Exxon-Mobil, the Cryostar re-liquefaction system EcoRel has been selected for the largest ever built Q-Max series LNG carriers. The capacity of these vessels, 265 000 m³, exceeds by far all that of all other LNG vessels ever built.

General considerations

The installation of a re-liquefaction system onboard a vessel is subject to spatial and operational constraints that do not exist in on-shore plants.

On shore re-liquefaction systems operate most of the time at constant load and almost continuously. On the vessel the volume of BOG varies quite a lot (laden voyage versus ballast voyage, sea conditions, tank spraying, etc.) and operation is not continuous since no re-liquefaction takes place during the loading or unloading of the tanks. The re-liquefaction process is thus stopped and restarted every 2 to 3 weeks depending on the route of the vessel.

To cope with these constraints Cryostar targeted low power consumption but also a simple, sturdy and easy to operate system allowing the process to be started quickly.

Cryostar's EcoRel concept is environmentally friendly. It performs full re-liquefaction of the BOG whereas other systems perform partial re-liquefaction and have to enrich the vented gas with methane in order to get a correct combustion before releasing it to the atmosphere.

Additionally, with the full re-liquefaction no nitrogen depletion takes place during the voyage so that nitrogen does not need to be added in the re-gasification terminal in order to maintain the gas heating value.

In fact LNG is a mixture of gases, methane being the main component. It also contains, in addition to butane, propane and ethane, up to 1% of nitrogen, depending on the loading terminal. The boiling point of nitrogen, under ambient conditions is -196°C , which is well below the -163°C temperature in the tank. This explains the high concentration of

nitrogen in the boil off gas: up to 30% compared to around 1% nitrogen in the LNG. (Almost no heavy hydrocarbons are present in the BOG since their boiling point temperatures are much higher than the LNG temperature).

Principle

The EcoRel re-liquefaction system relies on the principle of a closed nitrogen reverse Brayton cycle to produce the cold power needed to condense the BOG. The amount of cold production is proportional to the amount of boil off gas to be re-liquefied and is adapted by modifying the mass circulating in the nitrogen loop. The condensation temperature is a function of the boil off gas composition and of the selected pressure at which the condensation takes place.

The cycle includes 3 warm compression stages with intercoolers and after-coolers and one cryogenic expansion turbine combined in a single machine called a "componder", a machine developed by Cryostar in 1996.

The cycle also includes a counter current heat exchanger and the condensing part in which the cold power is exchanged with the BOG. Operating flexibility determined the choice of splitting the condensing part into two elements: a de-superheater and a condenser. This arrangement allows the BOG loop to be started quickly, and process flexibility for different BOG compositions.

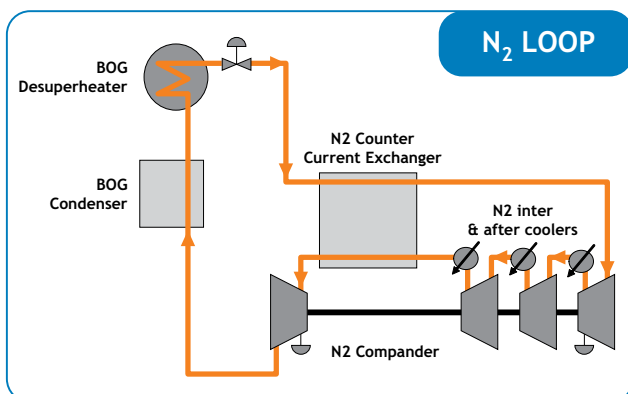
The BOG side consists of a two-stage compressor with inter-cooler, which relays the gas to the de-superheater and the condenser and then the return of the sub-cooled condensate to the tank.

Data

The quantity BOG needing to be re-liquefied on a Q-Max vessel is ~ 7 T/h. It requires a componder power of ~ 5.2 MW assuming -100°C gas inlet temperature at the BOG compressor inlet.

Control

Cryostar provides the process controls as well as the machine's control logic for full integration in the LNG carrier's central Integrated Automation System IAS. The process and the associated control



concept of the complete system have been developed with the help of static and dynamic simulation tools and have been validated by nitrogen liquefaction tests. The Cryostar deep knowledge of the design but also under off design conditions allows Cryostar to generate good and accurate machine models.

Machine

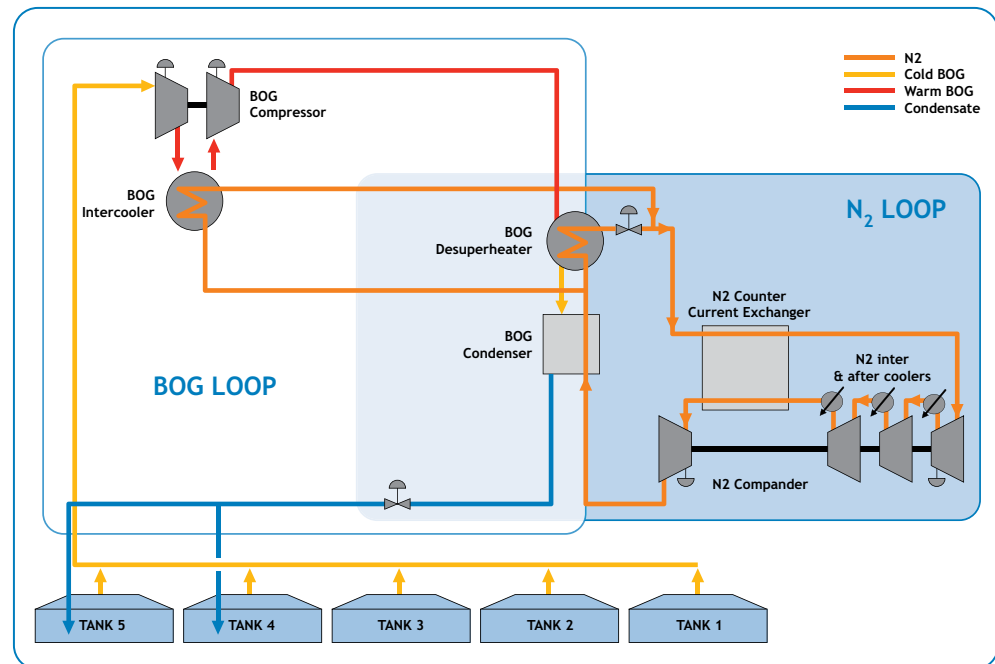
The two-stage BOG compressors are field-proven. In fact, they are similar to the ones installed on DFDE vessels except that their discharge pressure is lower for the re-liquefaction system.

The compander technology (3 warm compressor stages and one cryogenic turbine stage on a common single gearbox) has been proven since 1996 when Cryostar first implemented this integrated machine concept in air separation plants.

The motor is driven by a 6MW variable frequency drive in order to limit the inrush current. The ship, with very limited power generating capacities, operates in an island mode. The start up, which has a big energy consumption, is challenging each time.

Cryostar has developed and patented different concepts for the re-liquefaction of boil off gases.

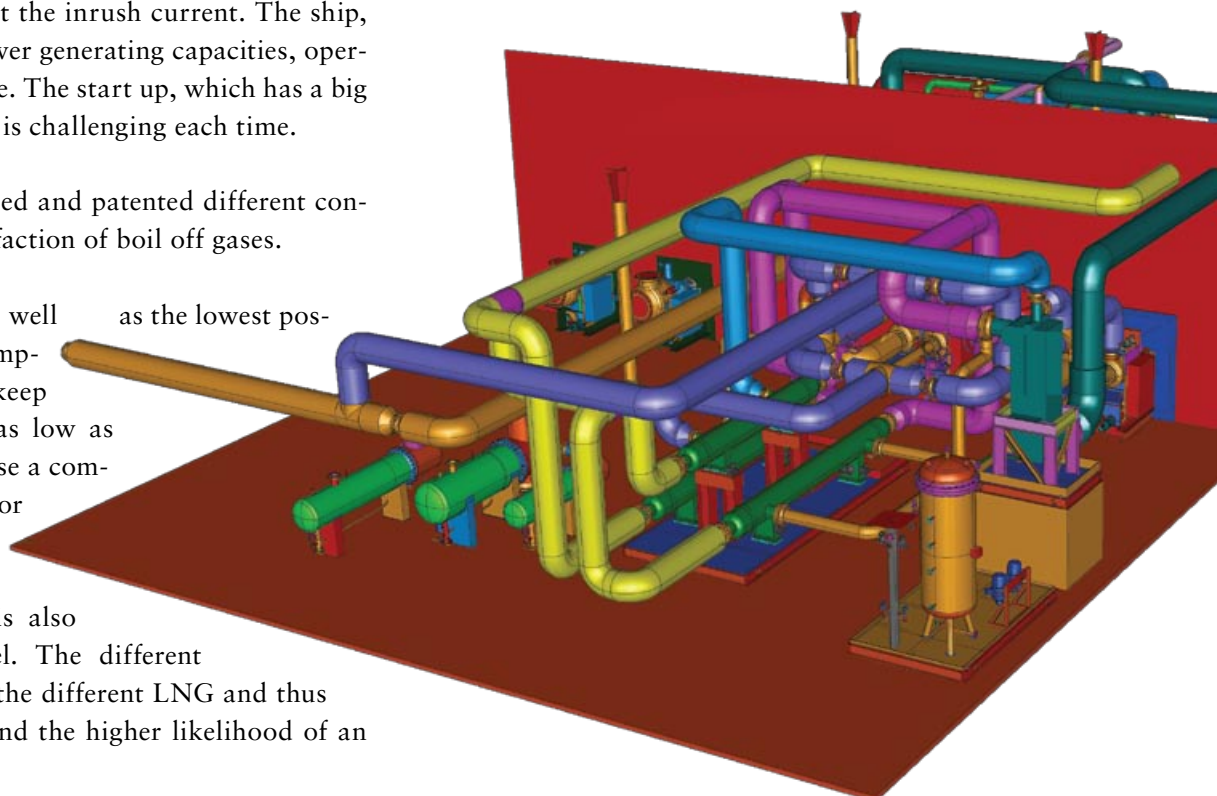
Low capital costs, as well as the lowest possible power consumption (in order to keep the operating costs as low as possible), are of course a common generic target for all re-liquefaction systems; but operational flexibility is also essential on a vessel. The different modes of operation, the different LNG and thus BOG compositions and the higher likelihood of an



electrical blackout on a vessel than in on-shore plants require a flexible and simple system.

Cryostar has reached a very good compromise with the EcoRel solution: quite low power consumption levels and a sturdy easy-to-operate system.

This concept could of course also be used for small on-shore projects. It can obviously be adapted depending on related operating constraints. For plants operating continuously additional features could also be implemented to reduce the operating costs.





How we tested EcoRel



Cryostar's quality control rules mean that all manufactured turbines, compressors or pumps have to be tested before delivery. This also applies to the rotating equipment for the "EcoRel", (Economic ecologic reliable boil-off gas Reliquefaction) system installed on LNG carriers. However the recurrent testing of a 6MW Componder (three combined compressor stages and one cryogenic expansion turbine on one common gearbox) required special considerations.

In addition to testing the machines, Cryostar also validated the reliquefaction process by liquefying nitrogen in a mockup installation.

One of the challenges that needed to be addressed to test the machinery was the electrical supply. A ship's electrical frequency is 60 Hz whereas the European grid frequency is 50 Hz. Cryostar had already the capability to drive motors up to 1.8 MW and 6000V at 60 Hz, but to drive the 6 MW 3300V componder motor, Cryostar had to invest in a 7.2 MVA variable frequency drive. Due to local power grid limitations, Cryostar also had to rent two 1 MW gensets for type testing of one unit at full power in order to demon-

strate the mechanical integrity of the machine. The recurrent testing power for all following units was limited to 4 MW.

All companders are tested with a dedicated oil system and inter-stage piping together with intercoolers and an after-cooler. Special piping and a special test procedure have been developed in order to combine the performance and mechanical running tests, performed within a closed loop filled with dry air. The resulting test conditions are close to nominal operating conditions onboard the vessel for the three compression stages.

This test allows the verification of the aerodynamic performance of all stages, the checking of the mechanical integrity of the machine under load and the confirmation that the anti surge system works as well as assuring the good functioning of all the instruments, and associated systems (gas seals, lube oil, etc...).

Such high load testing required high investment for the needed infrastructure and important resources for the recurrent complete unit assembly and installation, and also has a high power consumption.

Cryostar thinks that it was worth it, so that once installed on site the delivered machines are just perfect.

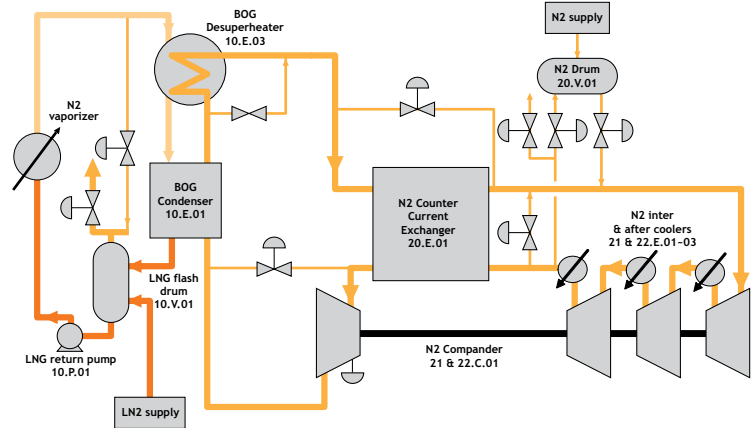
To validate the reliquefaction concept, Cryostar has built a full-scale mockup installation able to liquefy nitrogen using the equipment. The purpose of this test was to demonstrate that the equipment and associated control concept worked according to expectations. Since boil-off gas was not available, the system was tested with nitrogen.

The nitrogen loop, which is the cooling loop of the reliquefaction system, was identical to the one installed on a vessel from a functional point of view. The piping layout was adapted to the mockup installation. For the boil-off gas side, some modifications were made in order to represent the ship's operation. The core part of the system was kept similar to a ship's process and full equipment was used, i.e.: condenser, de-superheater, flash drum, and pump.

The liquefaction of nitrogen is more demanding than the liquefaction of LNG boil-off gas. It requires a lower temperature (as low as -183°C depending on pressure). This leads to a very cold temperature close to that needed for liquid formation at the turbine outlet, as we have to liquefy N2 with gaseous N2.

Simplified Process Flow Diagram N2 liquefaction test

— N2
— N2 to liquefy
— Liquid N2



The test was conducted in different steps in order to validate the sequences (start/stop/ESD), to tune the controllers and finally to confirm that the overall concept was sound.

After tuning the control loops, the installation worked well, and we were able to liquefy the expected flow of N2 with the expected power consumption. The testing was performed in summer 2007 and successfully witnessed by ship builder's and end user representatives on August 16th.

Cryostar does not compromise in the testing of its equipment even if it requires heavy investment – product quality always comes first.



EcoRel, how we developed it

When Cryostar first obtained the order for the 'design, procurement and construction of on-board re-liquefaction plants' the project team knew that it had to rely on first class tools in order to get the job done. This article examines three examples of such engineering design tools, explains the context in which they were used and shows how they contributed to the successful completion of the EcoRel project.

INDISS™

For the EcoRel project Cryostar was responsible for both rotating machinery performance and also for the performance of an entire plant. In order to build the on-board re-liquefaction plant it was necessary to master the process of the plant. For this purpose Cryostar used a high fidelity dynamic simulation platform provided by RSI Simcon (part of the IFP group) that was used in conjunction with the static process simulation tool HYSYS. The dynamic simulation tool called INDISS™ is designed in multi-layer component architecture. The open environment allowed Cryostar's engineers to implement their own proprietary components of the on-board re-liquefaction plant. Expanders, compressors, anti-surge protection and load sharing heat-exchangers and N2 make-up systems were all coded in the dynamic plant model.

The performance characteristics of the rotating machinery components of the plant were cross-checked and adjusted during the open loop performance test that was conducted at the Cryostar test facility.

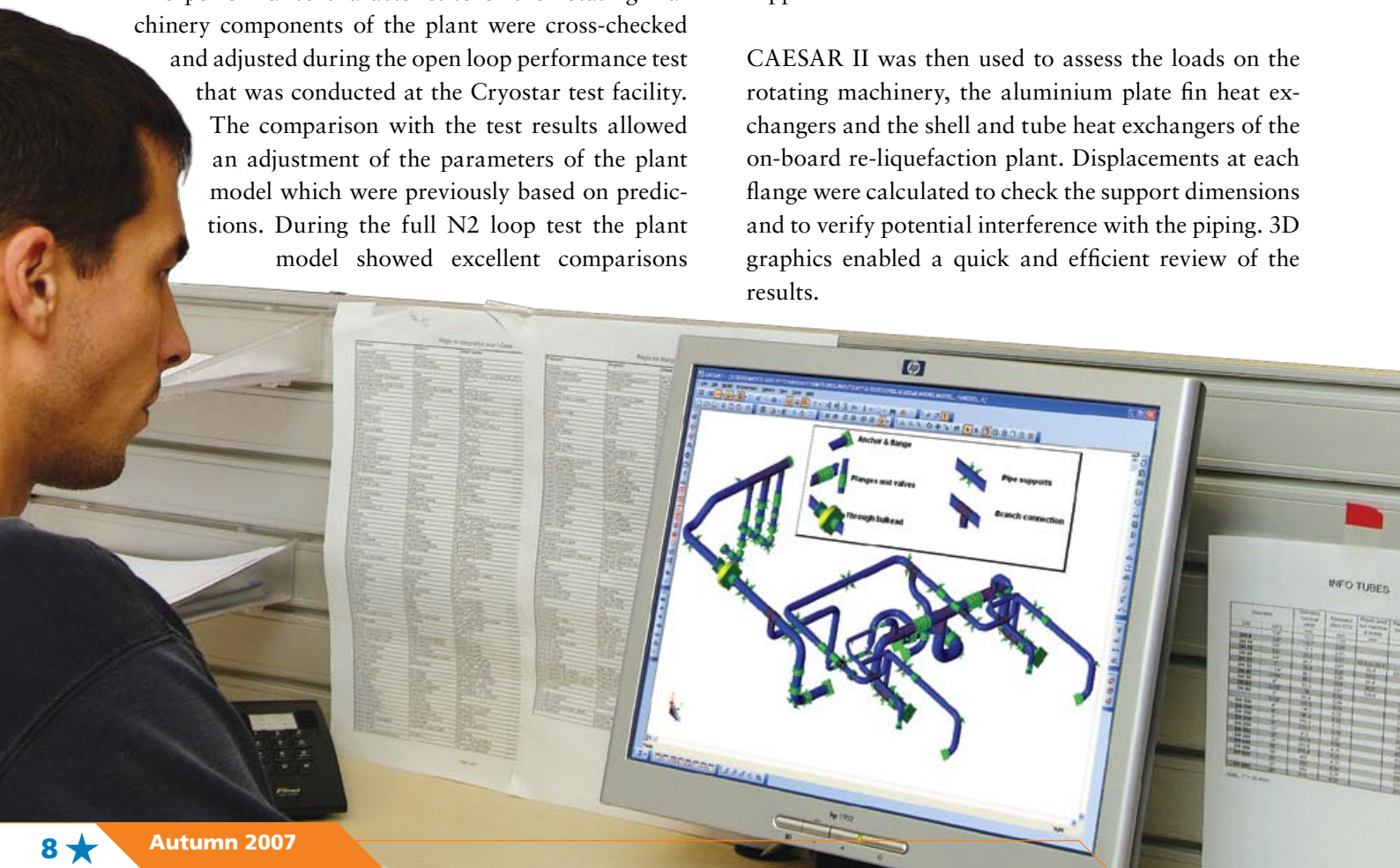
The comparison with the test results allowed an adjustment of the parameters of the plant model which were previously based on predictions. During the full N2 loop test the plant model showed excellent comparisons

with the measurements at the test bench and provided a useful learning tool for the operation of the plant.

CAESAR II

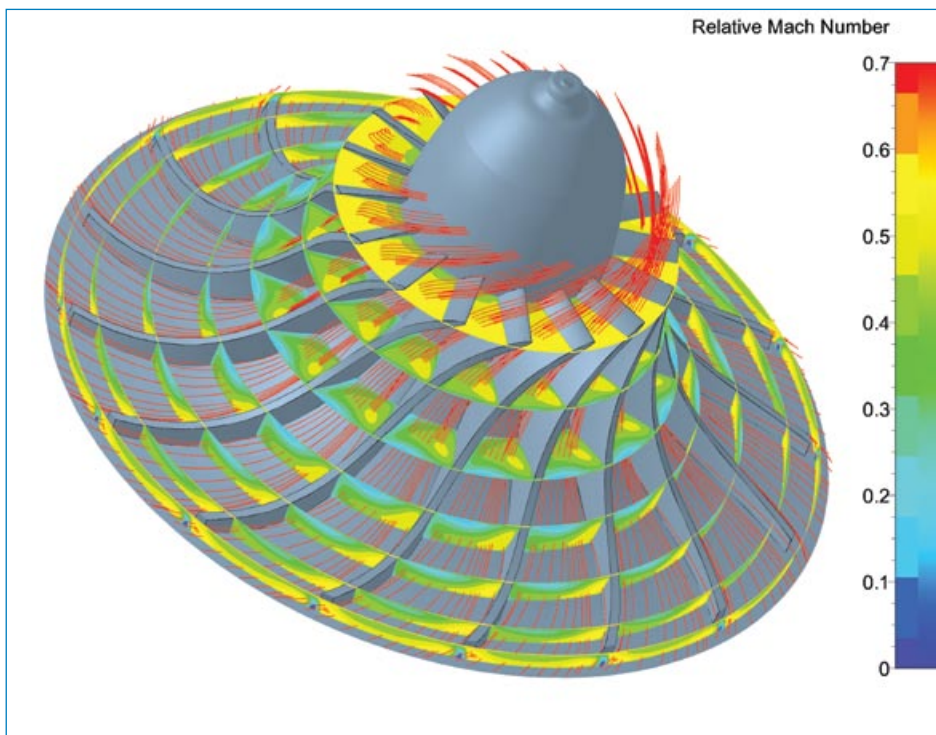
Another tool essential to the design of the EcoRel project proved to be CAESAR II (by COADE Engineering Software) a pipe stress analysis tool. The tool allowed a quick generation of the 3D model of the related piping for the on-board re-liquefaction plant based on a piping list, isometrics and the P&ID. A comprehensive material database with allowable stresses helped the user enter the piping material characteristics of the piping layout (ex: a variety of loads had to be applied to the model). Factors such as weight (including the thermal insulation), pressure and temperature gradients and shipboard accelerations as specified by the ship builders all had to be taken into account. Every element of the design was entered with the detailed supplier information.

CAESAR II was then used to assess the loads on the rotating machinery, the aluminium plate fin heat exchangers and the shell and tube heat exchangers of the on-board re-liquefaction plant. Displacements at each flange were calculated to check the support dimensions and to verify potential interference with the piping. 3D graphics enabled a quick and efficient review of the results.



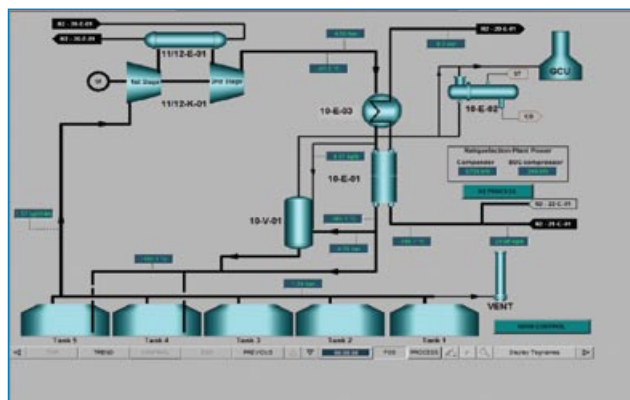
CFD

A third tool used for the EcoRel project was a Computational Fluid Dynamics code (CFD). The code from NUMECA allows the flow inside the rotating and stationary blade passage to be modelled based on a finite volume numerical method. For every calculation of a given passage inside the machine a structural mesh was generated with Autogrid™ and the 3D Navier-Stokes equations were computed with Fine/Turbo™ assuming smooth walls and adiabatic expansion or compression. Closure of the equations was given by the Spalart-Allmaras turbulence model. For the EcoRel project different flow features of the N2 compander were computed and the results were analysed using a 3D viewer.



A first CFD study concerned the static pressure field inside the nozzle blades of the expander stage. This computation allowed an estimation of the torque on the nozzle blades and helped to verify that the nozzle actuator was correctly sized for design and off-design duty.

A second CFD study examined the flow in the interconnecting piping between the compressor stages.



Stringent space constraints on-board ship resulted in having to optimise the aerodynamic performance of interconnecting piping with a small footprint. CFD helped to position flow straighteners inside the interconnecting piping in order to find the best compromise between the available space and the requirement of an undistorted flow field at the compressor inlet.

Further CFD studies analysed the performance impact of different compressor hub noses, different compressor diffuser geometries and the impact on efficiency of the tip clearance height. In addition to the design flow case off-design cases (low flow, high flow) were also studied. Finally the results were compared with test bench measurements.

The design of EcoRel in the given lead-time of the project would have been unthinkable without the extensive use of state of the art computer tools. Cryostar clearly gives itself the means to achieve its goals.

Cryostar and the LNG carrier market

Cryostar is the only supplier for the combined cryogenic machinery on board LNG carriers, selling the compressors as an integrated package with the cargo handling heat exchangers. Cryostar's unique know-how in this sector results in ship builders consulting Cryostar regarding proper sizing, interfacing and utilisation of the equipment.

A solution for all types of ship propulsion systems.

Until only a few years ago, machineries on LNG tankers were based on single steam turbine technology where the required steam was produced by two dual-fuel boilers, which use both boil-off gas and heavy fuel oil.

As environmental issues are becoming more and more important, ship builders and owners have started to look for alternative propulsion systems to move away from the less efficient steam turbine technology.

Consequently, and to anticipate the technological evolution, Cryostar has developed a combination of solutions applicable to any of the propulsion systems chosen for the future.

Irrespective of the selected ship drive system (conventional steam turbine, dual fuel engine, diesel electric drive system, gas turbine or diesel engine with liquefaction plant), Cryostar has the right combination of products for assuring reliable ship operation.

Cryostar is the only supplier for the combined cryogenic machinery for the cargo handling systems on LNG carriers with:

1. Boil-off Gas Compressors – used to keep the LNG tanks on board ship at the right temperature and pressure.
2. Gas heaters and vaporizers – used to warm up the boil-off gas which is then used to power the ship.
3. the re-liquefaction concept, EcoRel, combining a cooling plant and various components used in air separation and nitrogen liquefying plants (see main article).

Over the last few years, Cryostar has developed strong commercial and technical relationships with all major ship builders in China, Korea and Japan, but also in Europe. Orders were received from almost all major ship builders in the world, namely Daewoo, Samsung, Hyundai, Mitsui, Mitsubishi, Kawasaki, Universal, Hudong-Zhonghua, Chantiers de l'Atlantique (now Aker), Fincantieri and IZAR.

A large installed base and order book

As of today out of 237 ships in operation, there are Cryostar compressors and Cryostar heat exchangers on 196 ships. In addition, Cryostar has machines on order to equip 53 under construction. To which we need to add the 14 EcoRel re-liquefaction units for the Q-max ships presently on order.

As shown above, Cryostar has developed itself a strong position since the mid 70s. From being originally a supplier of machinery for industrial gas applications, the company has transformed into a more diversified organisation supplying other markets. Today, the LNG ship market is Cryostar's main business segment!



Infrastructure needed for EcoRel production

Lots of additional resources were needed to support the challenge of designing, producing, assembling, testing, and shipping the EcoRel units.

First, a new 1200 m² assembly hall was completed in February 2006 (see Spring 2006 edition) equipped with two 50-tonne cranes and eight one-tonne jib cranes. The total investment for this additional production structure was € 2.5 million.

Adjacent to this new workshop, a fully equipped new test facility was completed in Spring 2007. It is dedicated to the re-liquefaction units as well as large hydrocarbon turbines. The main characteristics of this test building are:

- 650 m² total test surface
- One 50-tonne bridge crane
- Two one-tonne jib cranes
- Two surface plates for machine testing
- 8 MW power supply
- Compressed air supply of 20,000 m³/h at 10 bar
- Cooling water circuit 550 m³/h with 6 MW cooling tower
- 6 MW variable frequency drive

The total investment was € 3.5 million

The test facility also includes a compressor room, an electric room, a computerized test commando room and a small conference room – in total some additional 300 m².



Events

★ November 13-16, 2007

Cryogen-Expo 2007, All-Russian Exhibition Center, hall No 70 "Moskva", Moscow, Russia.

★ November 27-29, 2007

ANGVA 2007 (the Biennial Conference and Exhibition of the Asia-Pacific Natural Gas Vehicles Association), BITEC, Bangkok, Thailand.

More info : www.angvaevents.com

★ February 20-22, 2008

Clean Heavy Duty Vehicle Conference, Hilton San Diego Resort, San Diego, California.

More info : www.cleanheavyduty.org

★ March 14-16, 2008

FUELLING PAKISTAN 2008 (International Exhibition on CNG, LPG & Alternative Sources of Energy), Fortress Stadium Lahore, Lahore, Pakistan.

★ February, 2008

AIIGMA (All India Industrial Gases Manufacturers' Association), New Delhi, India

★ March 10-13, 2008

23rd GASTECH, Bangkok International Trade & Exhibition Centre, Bangkok, India.

More info : www.gastech.co.uk



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 Contact: magazine@cryostar.com

★ CRYOSTAR Automation

Saint Julien d'Empare
 FR-12700 Capdenac
 info@cryostar.com
 Phone: +33 (0)5 65 80 20 20
 Fax: +33 (0)5 65 80 20 25

★ CRYOSTAR Brazil

Rua Tabapuã, 111 - 9e andar
 Itaim Bibi
 04533-010 São Paulo
 SP Brasil
 brazil@cryostar.com
 Phone: +55 11 3709-5697
 Fax: +55 11 3071-4579

★ CRYOSTAR China

Third building
 No. 17 Shanxian Road,
 Hangzhou - China 310004
 china@cryostar.com
 Phone: +86 571 8536 8331
 Fax: +86 571 8536 8409

★ CRYOSTAR SAS

ZI - BP 48
 FR-68220 Héisingue
 info@cryostar.com
 Phone: +33 (0)3 89 70 27 27
 Fax: +33 (0)3 89 70 27 77

★ CRYOSTAR Singapore

203 Henderson Road
 BLK B#10-09
 Henderson Industrial park
 S(159546) - Singapore
 singapore@cryostar.com
 Phone: +65 6276 7441
 Fax: +65 6276 7442

★ CRYOSTAR UK

Kea Park Close
 Hellaby, Rotherham
 South Yorkshire S66 8LB - UK
 uk@cryostar.com
 Phone: +44 1709 702 777
 Fax: +44 1709 702 771

★ CRYOSTAR USA East

5897 Colony Drive
 Bethelheim
 PA 18017 USA
 usa@cryostar.com
 Phone: +1 (484) 281-3401
 Phone: 1-800-483-1052 (for US and Canada only)
 Fax: +1 (484) 281-3402

★ CRYOSTAR USA West

9211 S.Greenleaf Ave
 Santa Fe Springs
 CA 90670 USA
 usa@cryostar.com
 Phone: +1 (562) 903-1290
 Phone: 1-800-483-1052 (for US and Canada only)
 Fax: +1 (562) 903-4511

★ Cryostar USA - Houston Office

5909 West Loop South,
 Suite 220
 Bellaire, TX 77401
 Phone: +1 (713) 661-6000
 Fax: +1 (713) 661-6075