FULL POWER, FULL PRESSURE, CLOSED LOOP TEST OF A NATURAL GAS TURBOEXPANDER

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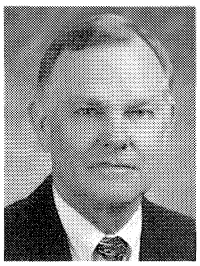

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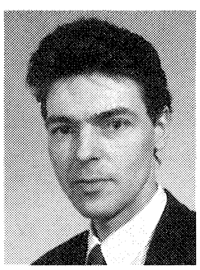

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ABSTRACT

An operator in the Danish part of the North Sea has identified as critical the ontime startup of a bridge module that is being developed as a "brown field" extension to a platform complex in the Danish sector of the North Sea. Project philosophy is to perform rigorous onshore testing and precommissioning activities in order to ensure no delays in delivery of contract quality natural gas from the module.

INTRODUCTION

Natural gas production from the Tyra field in the Danish sector of the North Sea is being increased. In order to accomplish this, a bridge module will be added to the Tyra West platform as indicated in Figure 1. The bridge module will contain the gas processing system and the required downstream compression equipment.

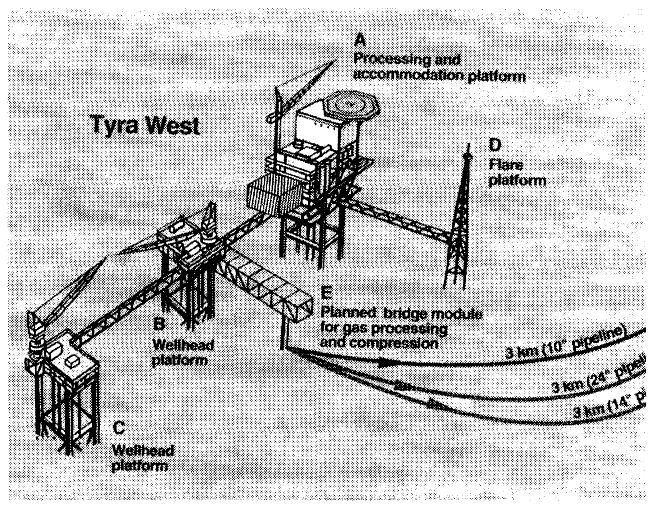

Figure1. Tyra West Platform Complex.

Because timely delivery of gas from the field is extremely important, the owners decided to carry out extensive onshore testing of all critical equipment. This decision was made, in part, to enable the resolution of the usual, minor startup and commissioning problems for much lower cost and expense onshore rather than in the offshore platform environment.

DEW POINT CONTROL PROCESS

Natural gas from production wells contains hydrocarbon and other liquids. In order to make this gas acceptable for pipeline transmission, it is necessary to remove these liquids to prevent condensation in the pipeline. The process of drying the gas to an acceptable level is referred to as dew point control.

An effective and economical process for dew point control involves cooling the gas, separating the condensed liquids, then reheating the dry gas. The turboexpander process, using the principle of nearly isentropic expansion of the gas, was selected for the Tyra West dew point control process. As shown in Figure 2, the natural gas is first cooled in a gas-to-gas heat exchanger. Condensed liquids are removed in a high pressure separator. In the turboexpander, the pressure drop produces a relatively large temperature drop causing formation of additional liquids. This liquid is removed in a low pressure separator. Gas from the low pressure separator enters the gas-to-gas exchanger to pre-cool the expander inlet flow. Heated gas is then compressed in a single stage, centrifugal compressor driven by the expander. The gas is then sent on to further compression before entry into the pipeline to shore. It can be seen that the refrigeration produced by the turboexpander is essential to the production of gas with the proper dew point specification.

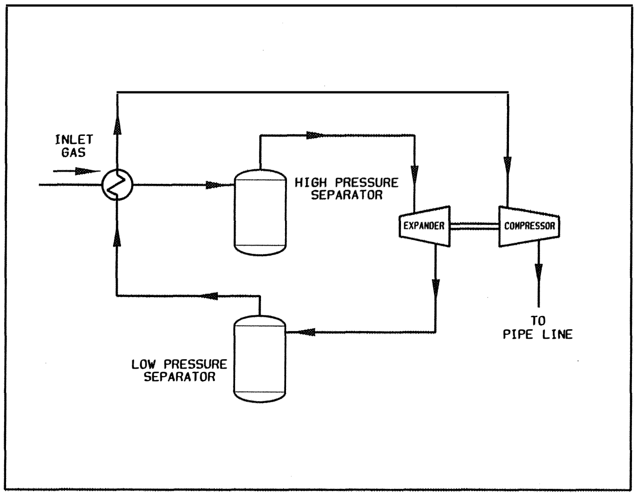

Figure 2. Dew Point Control Process.

For process reasons, the dew point control module uses two process trains and, therefore, two identical expanders are operating in parallel. Each expander consists of a 2000 hp, single stage, radial inflow expander equipped with variable inlet guide vanes for flow control. The expander is directly connected to a single stage centrifugal booster compressor. The proportions and general arrangement of a typical natural gas processing expander are shown in Figure 3.

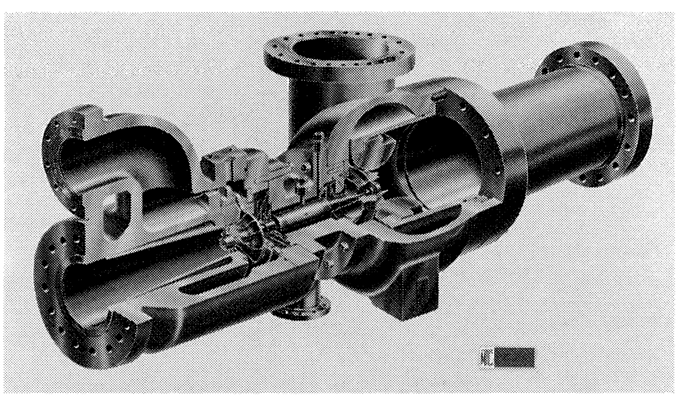

Figure 3. Typical Natural Gas Processing Turboexpander.

The two expander systems are designated as Frame 4 machines. During the detailed design phase, considerable attention was paid to such areas as rotordynamics, aerodynamic optimization, and matching of the expander and compressor.

The expander systems were designed and manufactured in strict accordance to the requirements of the Danish operating company and to the standards of the Danish Offshore Regulations. Det Norske Veritas provided independent certification of these requirements as part of the overall project plan. Factory testing of the expander systems included mechanical running tests in accordance with API 617 and expander and compressor performance tests in accordance with ASME PTC-10. One of the two expander systems is shown in Figure 4.

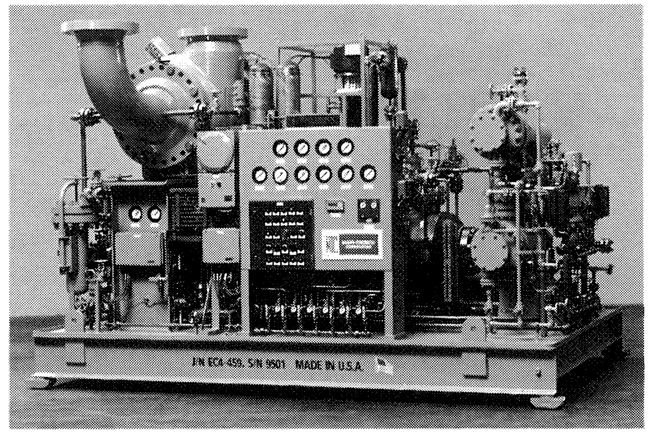

Figure 4. Tyra West Turboexpander System.

THE CLOSED LOOP TEST SYSTEM

In order to fulfill the goals of onshore testing of all critical components of the Tyra West bridge module, it was necessary to undertake something that had never been done before: a full power test of an expander system on natural gas in a closed loop. First, consideration was given to using a mixture of nitrogen and helium as a test gas. This approach was rejected since the diluting effects of the hydrocarbon process gas on the expander lube oil would not be simulated.

In order to perform this test, it was necessary to develop a closed loop test facility specifically for this project since no such facilities existed. After examining the available alternatives, it was decided to use the actual module process piping, vessels, and heat exchanger to the maximum extent possible in constructing the test loop. After a careful worldwide search for facilities capable of accommodating such a test, the coauthor's company was selected and placed under contract.

By using the actual process equipment and adding a test compressor, it was possible to compress the process gas from the booster compressor discharge, aftercool, and return it to the inlet of the gas-to-gas exchanger, forming a closed loop. The test compressor was a single stage, centrifugal unit driven by a 6000 kW, variable speed, electric motor. The arrangement of the resulting test loop is shown schematically in Figure 5.

The complete test system, consisting of process piping and equipment, expander system, test compressor, aftercooler, and test

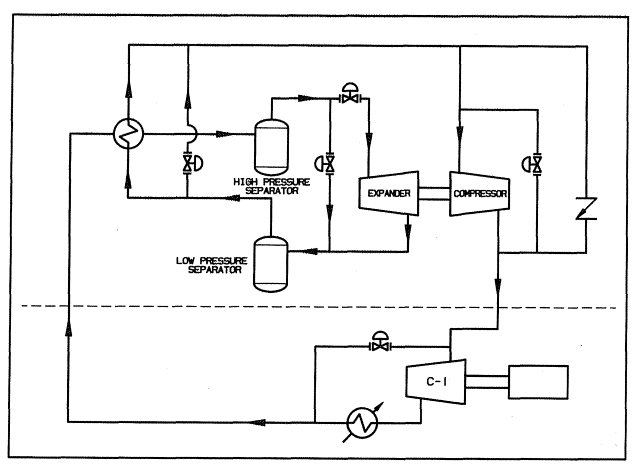

Figure 5. Closed Loop Test Schematic.

instrumentation and controls, was constructed within the large, indoor test facilities. Construction of this special test loop within the test hall facility was a very demanding task with a tight completion schedule. Process equipment and many large pipe spools had to be transported from Denmark and the United Kingdom to create this test loop. Considerable time and energy was spent managing the scheduling and logistics of the process equipment and expander system. This equipment was required for the closed loop test, but was also near the critical path for the assembly of the bridge module. In order to maintain the construction schedule of the bridge module, it was essential that the test be completed on time and all equipment shipped on schedule to the bridge module fabricator. Positioning the large separator vessels and heat exchanger and installing the piping, valves, and machinery on a two deck arrangement, required seven weeks of carefully managed work. The remote control panel for the expander system was installed in a control house within the test hall. The overall arrangement of the completed test loop is shown physically in Figure 6 and schematically in Figure 7.

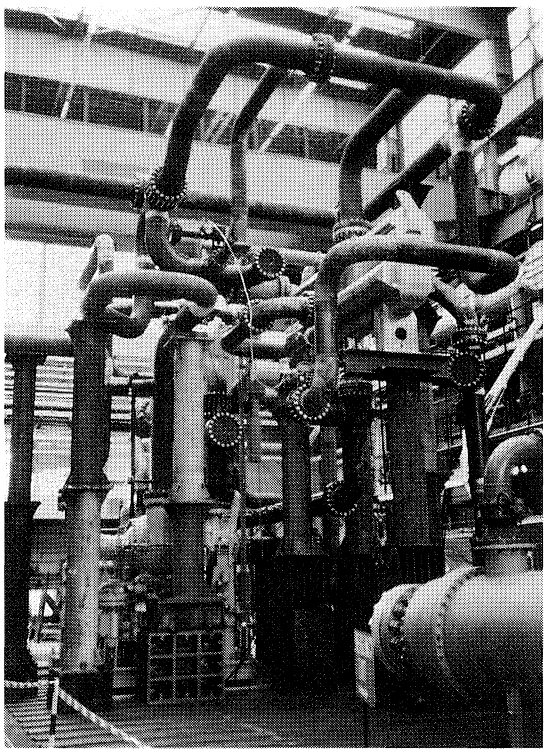

Figure 6. Overall View of Test Loop.

Upon completion of precommissioning of the expander system and test compressor, the test loop was pressure and leak tested using nitrogen gas.

THE TEST PLAN

The objective of the testing was carefully agreed prior to the test and was clearly stated in the Test Plan as follows: "The purpose of the testing is to aid in identifying, and rectifying, any expander system defects that could potentially cause delay in commissioning of the expander systems on the Tyra West Bridge Module." To accomplish this, the expander system was operated at conditions which simulated design point, normal startup, normal shutdown, off design, upset, and trip conditions.

Throughout the testing, the process conditions in the test loop and the expander operation were being monitored by extensive instrumentation. The main instruments were as follows:

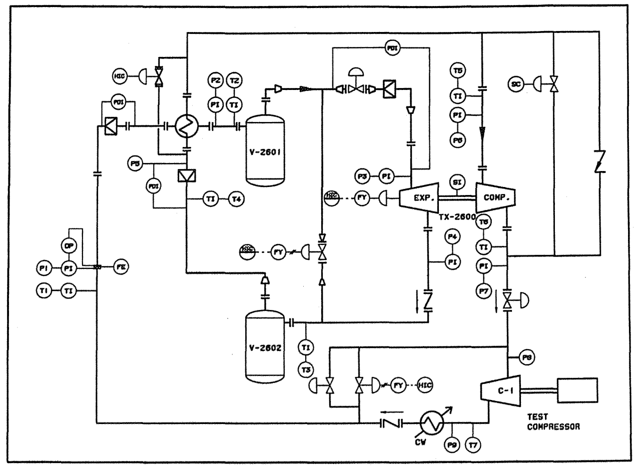

Figure 7. Closed Loop Instrument Schematic.

- ASME PTC-10 instruments for process pressure and temperature, logged every ten seconds during running. Note that measurement points were as designed into the process system and were not necessarily at the position specified in PTC-10. Process instrumentation is shown in Figure 7.
- Flow was measured by an orifice plate flowmeter, in accordance with PTC-10, and logged every ten seconds during running.
- Expander speed and two sets of X-Y vibration probes were continuously recorded on magnetic tape during running.
- Test compressor parameters, such as speed, inlet and outlet temperature, and pressure, were measured.
- Indication of lube oil viscosity at the inlet to the expander bearings was continuous.

Given the unique way in which the expander and its booster compressor are an integral part of the process, it was of particular interest to investigate the following questions during the test program:

- How will the expander respond to a full power overspeed trip; i.e., What is the duration of the coast down transient? Does the unit surge? Will expander vibration during the transient be acceptable?
- Since the lube oil reservoir is pressurized with process gas at expander discharge pressure of approximately 800 psig, how will the dissolved hydrocarbons affect the operating lube oil viscosity?
- Will shaft vibration amplitude and spectral content during full power, full speed running be acceptable?
- What will be the effect on the expander and process system of a full power surge of the booster compressor?
- Does the booster compressor surge control system operate properly during an upset?
- Are there any problems associated with rapid blowdown of the complete process system which would be required for an emergency shutdown on the bridge module?

NITROGEN TESTING

Before introducing natural gas into the test loop, a series of tests were run with nitrogen gas. The first such test was a proof test. This was done by pressurizing the test loop to 80 bara (1145 psia) and then testing for gas leaks. When all gas leaks were eliminated, the testing was continued. The test compressor and expander were operated and all controls were function tested.

With nitrogen gas in the test loop, the test hall represented a nonhazardous environment for electrical instruments and equipment. It was, therefore, possible to conduct a relatively detailed noise survey. The noise measurements were made by a sound and vibration consultant under contract to the Danish operating company. During the course of the noise test, the pressure in the test loop was adjusted so that the gas density was approximately the same as the design point, and the expander speed was varied around the design value. By these approximations, it could be anticipated that the noise generated by the expander system would be nearly equal to that at the design conditions. Comprehensive measurements of the sound pressure and sound power levels were made during several hours of high power running. By taking into account that the test hall is acoustically reverberant and the piping and vessels were not insulated, it is possible to use this data to assist in designing any sound treatment which may be required.

During the nitrogen testing, the booster was operated in hard surge for approximately 1.5 minutes at essentially full power and speed. Of particular interest is that during the 90 seconds of surge, the expander and compressor aerodynamic performance was logged every 10 seconds, and vibration signals from the four radial vibration probes and the speed probe were continuously recorded on magnetic tape. With these data, it was possible to verify the location of surge and analyze the dynamic response of the expander to full power surge.

Compressor performance, measured at the mid-time point of this surge event was compared to compressor performance data at the incipient surge point as measured during the factory ASME PTC-10 performance test. Shaft speed at the full power test surge point was 10,400 rpm (design speed is 10,500 rpm) and compressor inlet volume flow was 2005 cfm. Comparing this flowrate to the flow at incipient surge, 2090 cfm, confirms the location of surge at essentially full power and speed.

The dynamic and mechanical response of the expander to hard surge at full power was of particular interest. The data required for this evaluation were recorded on magnetic tape and an analysis of the vibration spectrum for all four radial vibration probes is shown in Figures 8 and 9.

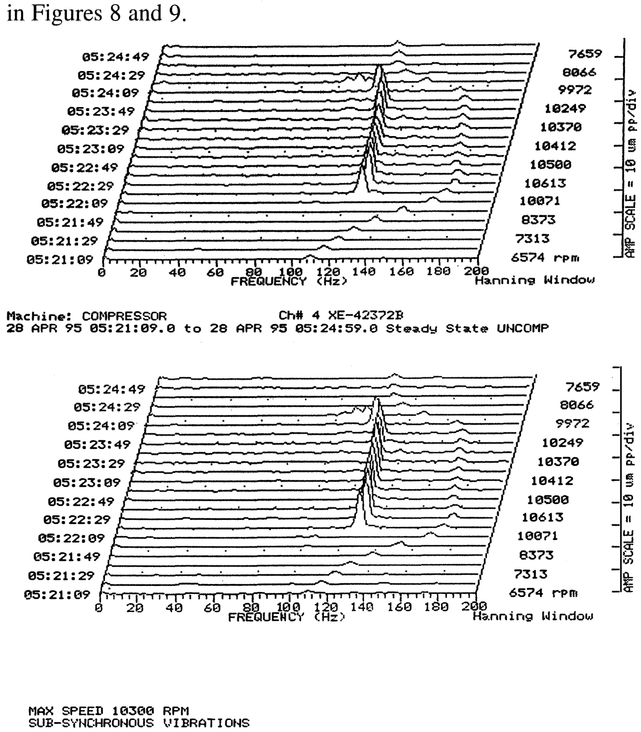

Figure 8. Waterfall Diagram for Booster Compressor Vibration Probes.

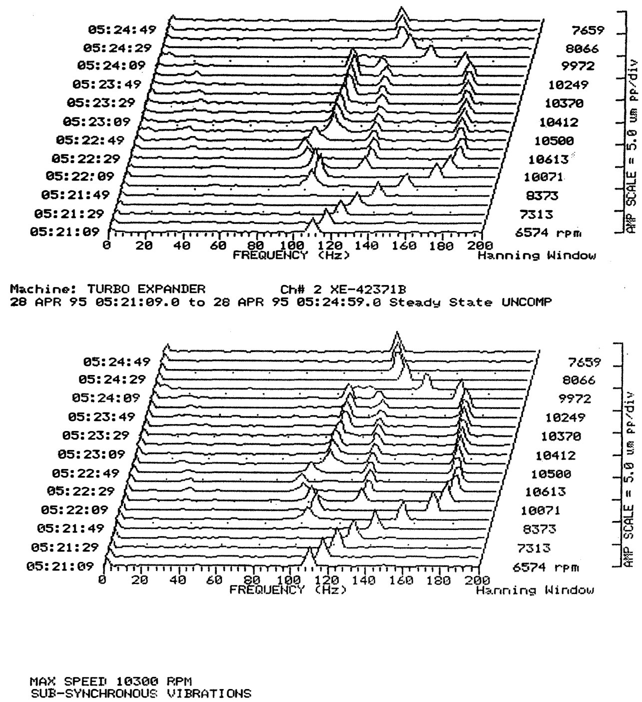

Figure 9. Waterfall Diagram for Expander Vibration Probes.

As shown in Figure 8, a "waterfall diagram" indicates vibration for the period of time from before the surge occurred until after the surge ended for the "X" and "Y" vibration probes near the compressor journal bearing. It can be noted that surge manifested itself as a subsynchronous component of vibration at 126 Hz with a magnitude of approximately 15 microns. This component suddenly appeared at 5:22:20 when the booster entered surge and disappeared at 5:24:10 when the booster exited surge. Both compressor vibration probes responded almost identically, as shown in Figure 8, and there was no effect on the synchronous vibration.

Vibration at the probes near the expander journal bearing during the same time period is indicated on the waterfall plot shown in Figure 9. Note that the subsynchronous vibration manifests itself as two peaks. One of the peaks is at 126 Hz and one at 105 Hz. The precise explanation of the 105 and 126 Hz peaks is not known at this time.

A very significant result of this event is that the total vibration level was below the alarm level on all probes during this full speed surge and caused no discernible distress to the expander. It can also be noted that incipient surge during the PTC-10 factory test did not manifest itself as a distinct subsynchronous component of vibration but as a broad, low frequency, response.

NATURAL GAS TESTING

After the nitrogen testing was completed, the test loop was pressurized with natural gas from the local distribution system. The loop was brought to 56 bara (815 psia) using a reciprocating booster compressor.

The test compressor was started, and flow was established through the expander with the expander bypass closed. The expander speed and power were increased to the design value and the operating point for the expander and compressor were compared with design values. The operating points for both the expander and compressor were shown to be within a few percent of the design values. This is of particular significance since this operating point must produce maximum expander and compressor efficiency, maintain proper surge margin, and accomplish this at a speed within mechanical limits.

Performance Data

The expander was operated at essentially design power, pressure, and speed for several hours. During this period of stable running, full performance data was taken every ten seconds over a ten minute period and the results were averaged. Analysis of these performance data, using accurate simulation of the gas mixture, indicates that the expander test point was very close to the design point, and the efficiency was between 91 and 93 percent. The contract guarantee value is 87 percent.

The compressor test point was between surge and the design point. By taking this into account, the compressor efficiency at the design point is estimated to be 81 to 84 percent. The contract guarantee value is 80 percent. The relation between the PTC-10 factory test results and the expander and compressor efficiency during the closed loop test is shown in Figures 10 and 11. The reason the closed loop test efficiencies are above the factory test results is felt to be attributable to Reynolds Number effects that were not accounted for in the factory tests.

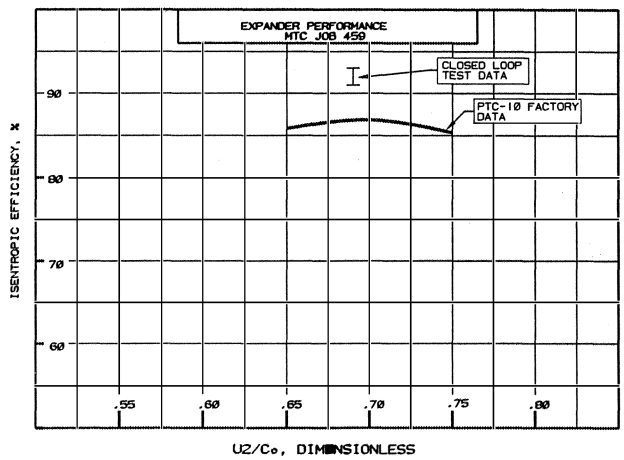

Figure 10. Turboexpander Efficiency.

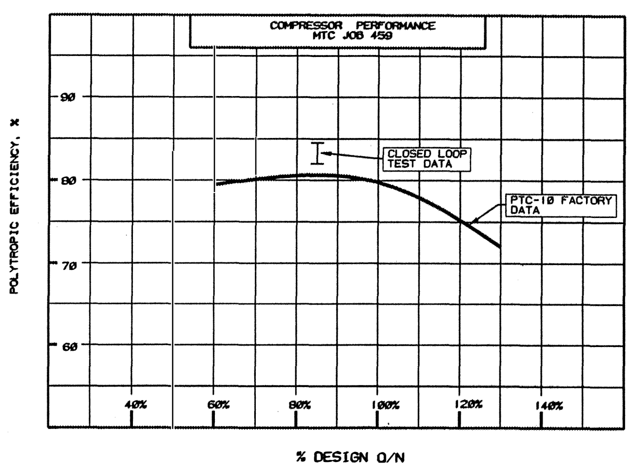

Figure 11. Booster Compressor Efficiency.

Operating Oil Viscosity

Natural gas processing expander systems utilize lube oil systems with reservoirs pressurized with process gas. Hydrocarbons naturally dissolve in the oil, lowering its viscosity. Depending on the pressure and composition of the process gas, the decrease in viscosity can be substantial. In order to determine the actual operating viscosity of the lube oil, an online viscosity meter was connected to a branch connection from the expander lube pump discharge line. This made continuous indication of expander lube oil viscosity possible during all phases of expander running.

The lube oil viscosity was measured at three different conditions: with the lube oil reservoir at atmospheric pressure with air as the diluting gas; with the lube oil reservoir pressurized with nitrogen; and with the lube oil reservoir pressurized with natural gas simulating the process gas.

As expected, the results of the viscosity measurements with the reservoir at atmospheric pressure and pressurized with nitrogen agreed with published data. The viscosity *vs* temperature for the ISO Grade 46 turbine oil is shown in Figure 12.

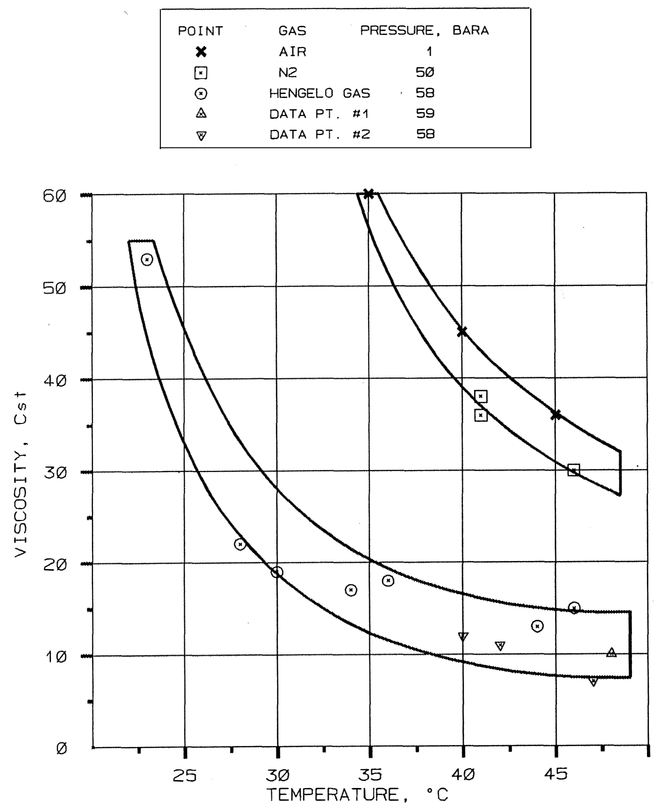

Figure 12. Turboexpander Lube Oil Viscosity.

To determine the effect of dissolved hydrocarbons from natural gas on viscosity, the first step was to measure the viscosity under pressure with the relatively lean gas as taken from the local gas distribution system. These data are shown as "Hengelo gas" in Figure 12. The next step was to slowly add 90 kg (200 lb) of propane to the test loop in two increments (data point #1 and #2). This quantity of propane added to the loop brought the propane plus composition of the test gas up to 2.8 percent which is approximately the value of the actual process gas. It should be noted that the addition of this quantity of propane had a relatively small effect on the viscosity in the temperature range of interest (35° to 45°C). The range of oil viscosity was found to be acceptable for all test gas compositions and operating conditions. Overall vibration levels were well below that specified by API 617, and the vibration spectrum was essentially unchanged for all operating conditions.

Overspeed Trip Transient

A full power overspeed trip was demonstrated by suddenly opening the expander inlet guide vanes with the expander operating at approximately 11,000 rpm. As the speed rose to 11,500 rpm, the expander inlet trip valve closed in 0.5 seconds. The expander speed trace taken from the magnetic tape recorder shows that the speed decreased from approximately 11,500 rpm to less than 1000 rpm in under two seconds. This shows, dramatically, that the modern gas processing turboexpander is a very high power density, low inertia machine which will decelerate surprisingly rapidly if the flow to the expander is suddenly stopped. No booster compressor surge was detected during the trip transient, and all aspects of mechanical operation were found to be acceptable during and after the trip.

It is also interesting that the expander speed decreased to approximately 500 rpm within six seconds after the trip and then remained at this value. The stabilization of the expander speed at 500 rpm is known as "windmilling" and is caused by gas flow through the booster compressor. This flow results from the expander bypass which opens on expander trip. With reference to Figure 5, it can be seen that flow arriving at the booster compressor inlet can take two routes. Most of the flow bypasses the compressor through the bypass check valve. However, depending on compressor and piping details, the small flow which goes through the compressor can be sufficient to produce forward rotation at between zero and 600 rpm, depending on expander bypass flowrate. This slow rotation is acceptable as long as the lube system is in operation.

Rapid System Blowdown

During certain emergency conditions on the platform, the process system must be depressurized rapidly. As discussed previously, light hydrocarbons are dissolved in the expander lube oil. It is well known that if the initial oil reservoir pressure is high enough and the depressurization rate is rapid enough, that considerable foaming will occur in the lube oil due to release of dissolved gas. Until this test, no accurate testing had been done to determine the degree of oil foaming. Therefore, no data were available as to the loss of lube oil from the reservoir, if any, during a rapid blowdown.

With the test compressor and expander stopped and with the J-T valve, booster compressor surge valve, and expander guide vanes full open, the process system was depressurized at a rate approximately equal to the maximum expected rate on the platform.

The system pressure *vs* time is shown in Figure 13. It can be noted that the pressure decreased rapidly from 61 bara (885 psia) to 7.0 bara (102 psia) in 6.5 minutes. The pressure was held at 7.0 bara for 14 minutes and then the blowdown was continued to essentially atmospheric pressure in an additional 12 minutes. The total blowdown time was, therefore, 18.5 minutes. No rotation of the expander or other adverse effects were noted in the expander system.

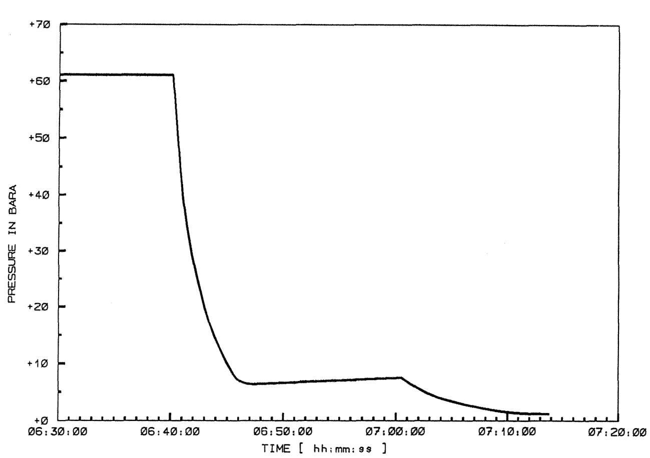

Figure 13. Process Blowdown Curve.

After the blowdown was complete, the expander and compressor casing drains were opened to determine if lube oil had migrated into the machine casings. Approximately 0.25 gallons of oil was found in the expander casing, and approximately 25 gallons was found in the compressor casing. When the test loop was later disassembled, no oil was found in any other piping or process equipment.

The bulk of the lube oil had entered the compressor casing, because the expander lube oil reservoir was depressurized through a vent line that connects the top of the reservoir to the booster compressor inlet line. Oil foam had been carried through this line on blowdown and deposited in the compressor casing. Since this oil accumulation was considered undesirable, a valve arrangement was devised which directs any oil foam into a suitable drain system rather than the compressor casing on rapid blowdown.

RESULTS AND CONCLUSIONS

The nitrogen and hydrocarbon running of the turboexpander has provided valuable data about turboexpander operation and its interaction with the process system.

The principal results and conclusions are as follows:

- More than 40 hours of expander operation were accumulated on full pressure natural gas; 35 hours of running were at or above design speed and power.
- Full power booster compressor surge was demonstrated with no detrimental effects.
- ISO Grade 46 lubricating oil was shown to be acceptable for expander operation on nitrogen gas and a range of mixtures of natural gas.
- Full power overspeed trip was accomplished with no adverse effects.
- Expander and booster compressor efficiencies were shown to be above the contract guarantee values.
- Noise data were taken during full speed, high power operation on nitrogen gas.
- Lubricating oil was shown to displace from the expander reservoir into the booster compressor casing on rapid blowdown. A vent piping modification was devised to prevent this from occurring in the future.
- Mechanical operation of the expander and its auxiliary equipment was flawless during all phases of testing.
- The maximum possible confidence has been obtained in order to commission the turboexpander system successfully offshore.

ACKNOWLEDGMENTS

The authors would like to acknowledge the active cooperation and support of Poul Nymand and Neil McLean of Maersk Oil and Gas.