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ABSTRACT

The Wintershall's Maria subsea project consists of three main pipelines to be installed. The scope of this thesis is to identify and evaluate different approaches to subsea commissioning of Maria's three pipeline systems and select a commissioning mythology for each pipeline system and identify points for optimization. The pipeline commissioning in this thesis is defined as the dynamic part of making a system ready for operation.

The three pipeline systems are a gas lift, a water injection, and a production pipeline system. Gas is intended for a well-lifting purpose, injected into the well stream downhole to decrease the density of produced oil. Water is injected to maintain reservoir pressure, increase production rate and extend field operating life. The production pipeline transports hydrocarbons to the Kristin production unit for processing. The pipeline systems are presented in this order with suggested commissioning procedures. To evaluate the different commissioning procedures, chemicals used and necessary equipment is also identified. An evaluation sheet has been designed for visualization and summation of evaluated points. This was used both to evaluate commissioning procedure and to identify points of optimization.

Gas lift pipeline system

The main objective to the gas lift system review was to find a suitable de-watering procedure. De-watering should be as cost effective as possible while achieving the specified dryness inside the pipeline. Three options of drying technique were identified, discussed, and evaluated. It was found necessary to divide the de-watering procedure into two steps for optimization. The two steps of the de-watering procedure are pig-sweep train combined with following nitrogen drying. A calculation has been performed to optimize the volumes used in the pig-sweep train. The selected procedure will optimize the drying efficiency and maintain integrity.

Water injection pipeline system

The main objective related to the water injection system was to identify and evaluate a procedure to remove air trapped in the pipeline. The main criteria are time efficiency and a good result. Two options were identified, displacement by foam pigs, and direct flushing. Both procedures were found viable, but the selected method for optimization is direct flushing. The necessary flow velocity for flushing has been calculated, and pump capacity is evaluated. The calculation found that the velocity of flushing should be at least 1.2m/s to provide a plug flow that will flush trapped air out of the pipeline. The flow calculation shows that one of the two pumps intended for use is sufficient to achieve the plug flow criteria. For optimization, both pumps should be run together for a more effective flushing effect.

Production system

The main objective to the production pipeline commissioning was to identify a commissioning procedure efficient on time and still preserve the integrity of the system. The main criterion is to perform a safe start-up and cause as little influence on the Kristin process system as possible. Four methods of commissioning were identified as viable. The preferred option of commissioning is to use a 250m³ slug of diesel between displacement pigs to displace the production line and drive out residues of water. The diesel slug and pig train are suggested to be displaced by the first production of hydrocarbons.

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SPECIFIC TERMS, DEFINITIONS, ACRONYMS, AND ABBREVIATIONS

CDT	cool down time
DEH	direct electric heating
DN	diameter nominal
DPE	double piston effect
FEED	front end engineering and design
FPU	floating production unit
GL	gas-lift line
HFT	hydrate formation temperature
HSE	health safety and environment
ID	inner diameter
ILT	in-line tee
LP	low pressure
MEG	monoethylene glycol
NCS	Norwegian continental shelf
OSPAR	Oslo and Paris Conventions
PE	polyethylene
PL	production line
PLEM	pipeline end manifold
PLONOR	pose little or no risk (to the environment)
P&ID	process and instrument diagram
RB	riser base
ROV	remote operated vehicle
ROVCON	remote operated vehicle connection tool
R.H.	relative humidity
SPS	subsea production system
SRP	sulphate reduction package
SVP	saturated vapor pressure
TEG	triethylene glycol
TLP	tension leg platform
WI	water injection line
WVP	Water vapor pressure
XOV	crossover valve

MATHEMATICAL SYMBOLS

A	pipeline inside cross section area
$A_{(y)}$	Area cross section at filling level y
A_{cs}	Area cross section calculated
A_i	inside area of pipeline wall
$\Delta P_{friction}$	pipeline pressure loss due to friction
$\Delta P_{hydrostatic}$	hydrostatic pressure
δs	sublayer thickness
d	inner diameter
ϵ	pipeline roughness
ε	relative roughness
f	friction factor
g	gravity constant
Δh	height difference
l	length
$N2_{volume}$	Volume to fill with nitrogen
P_{atm}	atmosphere pressure
P_{pig}	expected pressure to displace pigging train
$P_{pipeline}$	pipeline pressure
ρ	density
ρ_w	density water
$\rho_{N2(gas)}$	density nitrogen gas at 0˚C
$\rho_{N2(liquid)}$	density liquid nitrogen at -195.8˚C
π	circle constant Pi
Q	volume flow
Re	Reynolds number
R_{wx}	Residual water in the complete system
r	inside radius
T	temperature
t	pig bypass thickness
τ_w	shear force acting on the inside pipeline wall
u_w	friction velocity
V	inside pipeline volume
V_{bypass}	total bypass volume of a pig run
V_{bx}	bypass volume of pig depending on distance travelled x
V_{Gas}	gas volume
V_{MEG}	MEG volume
$V_{pipeline}$	pipeline volume
V_s	slug volume
$V_{water\ residue}$	water residue volume
v	velocity
υ	kinematic viscosity
y	distance in height from inside bottom of the pipeline
μ	dynamic viscosity
$W_{content}$	water content
$W_{cont\ X}$	water content depending on distance travelled x

LIST OF FIGURES

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ACKNOWLEDGEMENTS

The topic of this thesis is selected to approach an actual industry challenge: optimization of subsea pipeline commissioning. With access to the Wintershall's Maria project data, calculations and problem definitions are related to an up to date 2015 subsea project. However, much of the data used in this thesis has origin from the front end engineering and design (FEED) part of the project and may require a correction to the actual data and facts for construction. The thesis is not defined as a part of the work on the Maria project but a standalone document on the topic. The goal of the thesis was to gather insight on commissioning procedures, evaluate different approaches to commissioning and suggest how to make each pipeline systems ready for start-up and identify points of optimization.

I will especially like to thank John Kåre Smistad [1] and Bård Owe Bakken [2] at Wintershall Norge for excellent support throughout the thesis. I will also thank for the support, follow up and discussions with Professor Eiliv Janssen [3] at the University of Stavanger. I will also like to thank Per Christer Røed [4] and Lars Topnes [5] for an introduction to subsea commissioning and a yard tour at IKM Testing on commissioning equipment. This gave a much better perspective on the scope of work related to subsea commissioning.

1 INTRODUCTION

Commissioning of subsea pipelines are important and intricate operations, and one of the most important activities before start-up of a new subsea field. The commissioning procedure must be designed to best accommodate specifications to each pipeline system to ensure a safe and efficient start-up with minimal impact on the environment. Already at concept selection one should have commissioning in mind.

Commissioning of subsea pipelines is a time consuming, expensive and demanding task. Planning in front of a subsea commissioning is utterly important. Failure in a commissioning procedure may have vast consequences. Hydrate formation, poorly performed cleaning or mixture of chemicals that are not intended to mix may compromise the lifetime of the pipeline, completely block or even result in disabling the pipeline for use. Environmental hazards, additional cost, integrity loss of the system and safety to personnel in operation are also some issues that must be considered. Commissioning of subsea pipelines varies with the intended use of the pipeline, material properties of each pipeline, chemical use in commissioning and availability to the pipeline ends. Length and size of each pipeline do also have an impact on the decision making, internal volumes changes and other methods of approach may be more effective on larger/smaller pipelines. Since properties vary on each installation, so will the commissioning procedures.

There is no final answer for a perfect commissioning procedure, an operation may be environmental friendly, but the integrity of the system during commissioning could be compromised by less effective chemicals. Other commissioning procedures may be safe and conservative, but the cost and time consumption of this procedure can be extensive. Since all commissioning procedures differ, there will always be room for improvement and new ideas. In this thesis, experiences from different performed subsea commissioning operations are used as background material. New ideas, combination of commissioning techniques and calculations are used to establish options for commissioning procedures. The options are evaluated against each other and sometimes combined to conclude with a preferred procedure.

1.1 Objective

The objective for the thesis shall be limited to: From pipelines are installed on the seabed, to and including the production start-up. The part of preparing all pipelines for the start-up is described as pre-commissioning and commissioning. Pre-commissioning relates to the part from after each pipeline is laid down on the seabed and the procedure of flooding, cleaning, gauging and pressure testing before final commissioning. The next part of the installation procedure is the tie-in procedure where all parts of the subsea system are connected. This part is not included in the thesis other than the assumption that some seawater ingress is unavoidable at connection points. After the tie-in is completed, commissioning of subsea pipelines must be performed to accommodate material specification and process properties of each pipeline system and to make them ready for start-up. The intention is to come up with different operational sequences to overcome the commissioning demands, and to evaluate the different solutions and come up with a preferred method of commissioning on the Wintershall Maria development.

1.2 Method

The first part of the thesis is a familiarization with the different pipeline systems following identification and to call attention to specific needs to each pipeline system. Necessary equipment selected for commissioning and pre-commissioning is presented. Chemicals intended to be used in commissioning are evaluated. The volumes should be optimized, and discharges should be limited to biodegradable chemicals. As a part of the preparation for commissioning, pigging is evaluated for the selected pipeline systems.

The thesis is divided into three main chapters one to each pipeline system that are; gas lift, production and water injection system. Pre-commissioning procedures are suggested related to each pipeline system, illustrated and described. Battery limits to each system are illustrated to give a visual view of the interfaces between Statoil and Wintershall.

Commissioning procedures are suggested based on earlier performed operations and field proven techniques. Commissioning techniques is gathered from published documents regarding commissioning, interviews with executing companies and operating company experiences. Selected alternatives are evaluated, and calculations performed where found necessary to help the evaluation. A priority list has been developed to help deciding on the best methodology.

1.	Safety to personnel in operation
2.	Environmental consideration
3.	Integrity of procedure
4.	Interface issues to host
5.	Cost

Table 1.2-1: *Priority list on performing commissioning*

The priority ranking is selected to ensure that safety to personnel and environmental consideration is a point of focus. When these considerations are preserved, the integrity of procedure is valued highest. Interface issues to hosts are ranked higher than cost because an interference with regular production easily exceeds the cost of commissioning.

1.3 Introduction to the Wintershall, Maria development

The Maria field is a discovery with Wintershall as the operator on the Norwegian continental shelf (NCS). Wintershall, Centrica, and Petoro are license holders of the discovery. Maria is located in the Haltenbanken area, northwest of Trondheim. The discovery from June 2010 was found in an area with 300m water depth. The field is estimated to contain 180 million barrels of oil equivalent [6] and was evaluated to be a too small for a standalone development. The preferred development solution was to connect production from the reservoir to already existing infrastructure in the area.

The Maria field will be developed as a subsea field. The subsea production system (SPS) consists of two templates. Maria template G, (located north) and Maria template H (located 3km further south). Each template contains four well slots, two production wells, and one water injection well. One well slot at each template is spare for future needs, either as a producer or a water injector.

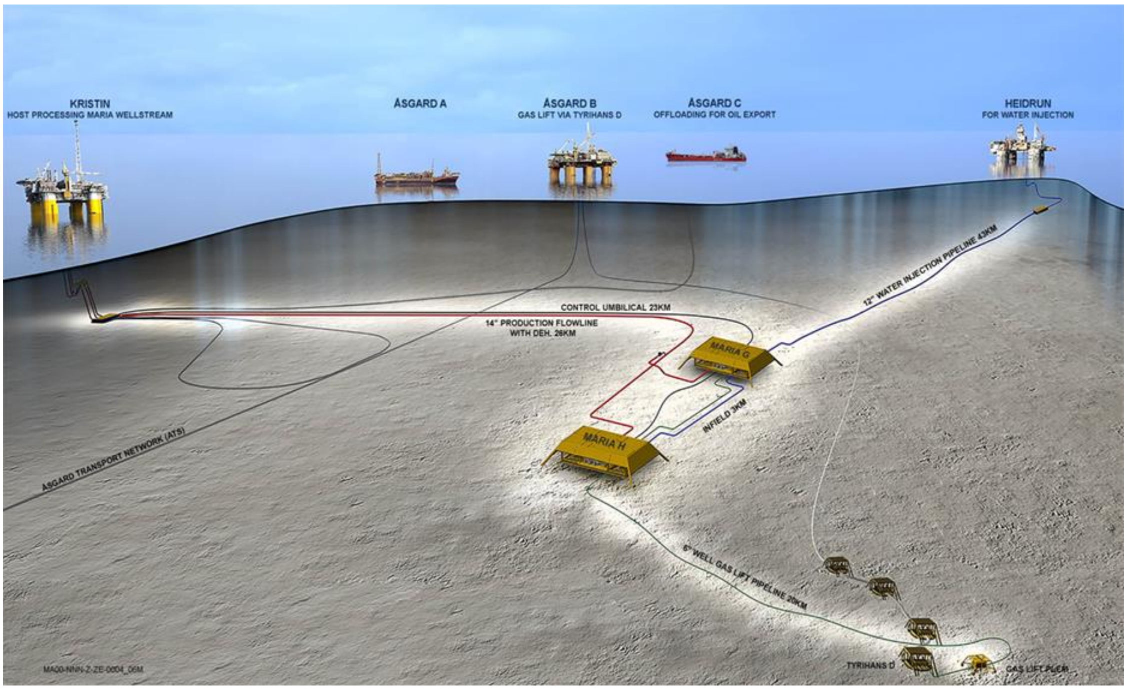


Figure 1.3-1: *Subsea layout* [6]

The tie-back solution of Maria is quite complex. The Kristin floating production unit (FPU) is to be used as the host platform, produced oil and umbilical are tied back to Kristin 26km northwest. Produced water for injection is provided from Heidrun tension leg platform (TLP) 43km northeast. Gas for gas lift purposes is provided from the subsea Tyrihans field 20km southeast. Tyrihans is supplied with gas from Åsgaard B production unit [7]. The operator on all infrastructures mentioned is Statoil.

2 STRUCTURES, EQUIPMENT, CHEMICALS, AND PIGGABILITY

2.1 Pipeline design

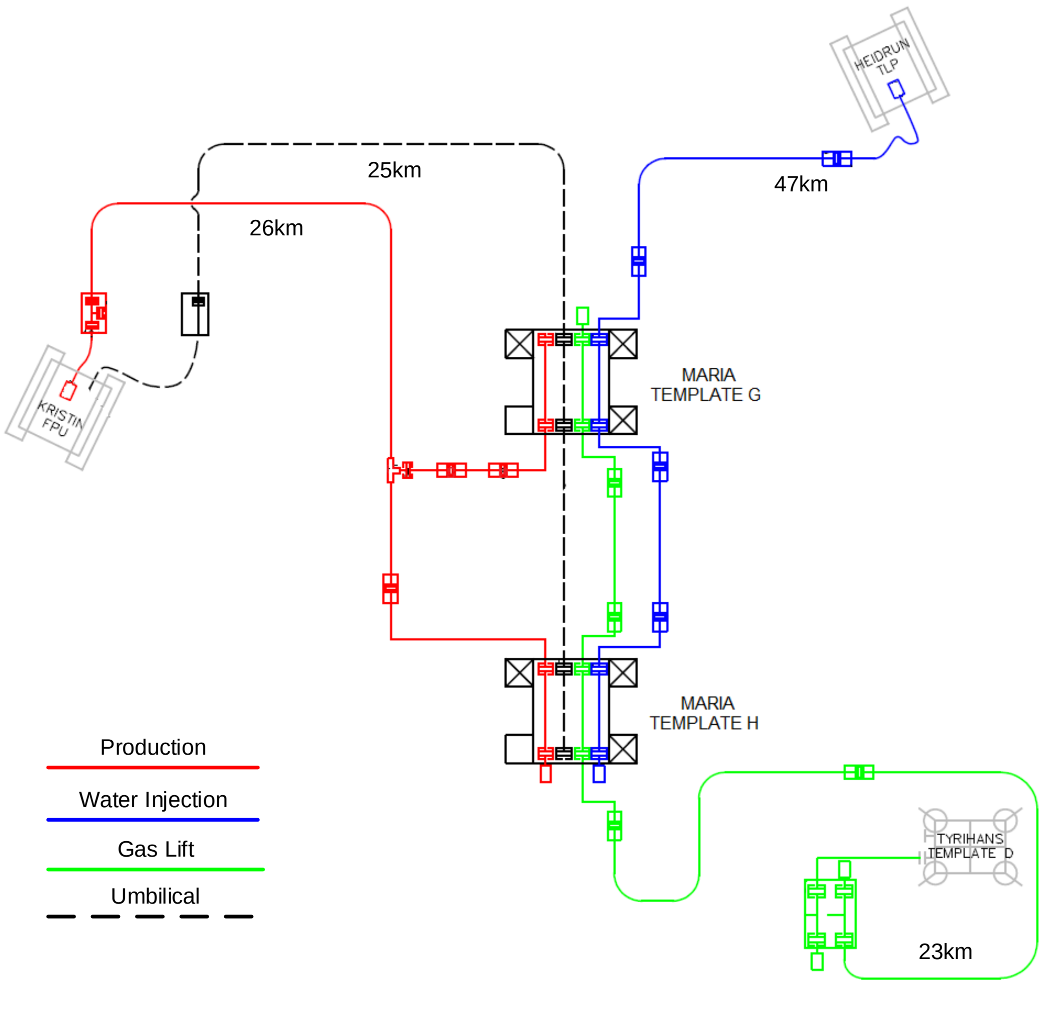


Figure 2.1-1: *Maria subsea Schematic*

The subsea schematic shows the main pipelines for the Maria development. Pipeline specification from FEED [7] is listed to each pipeline system. The total volume of the system is calculated and total main pipeline length. The calculation is performed by collecting data from SPS supplier and pipeline data from the FEED. Some small deviation must be expected since the production drawing is not completed.

$$V = \sum \frac{\pi}{4} * (d)^2 * l$$

Total volume (V) is calculated by summing all pipeline parts of each system. The pipeline sections are assumed to have zero out-of-roundness, and are represented by inner diameter (d). Volume reduction because of bends is not accounted for. Length (l) of each section is based on design basis [7], and some sections are assumptions based on similar installations. Calculated volume is expected to be larger than the actual internal volume of the pipe sections.

2.1.1 Gas lift pipeline

The gas lift line is running from the Tyrihans template D to the Maria Field with an approach from the south. The main plan for the commissioning is to leave this system filled with a dry gas with a dewpoint of -18˚C. The gas should preferably contain as little oxygen as possible because of corrosion danger combining oxygen with hydrocarbons.

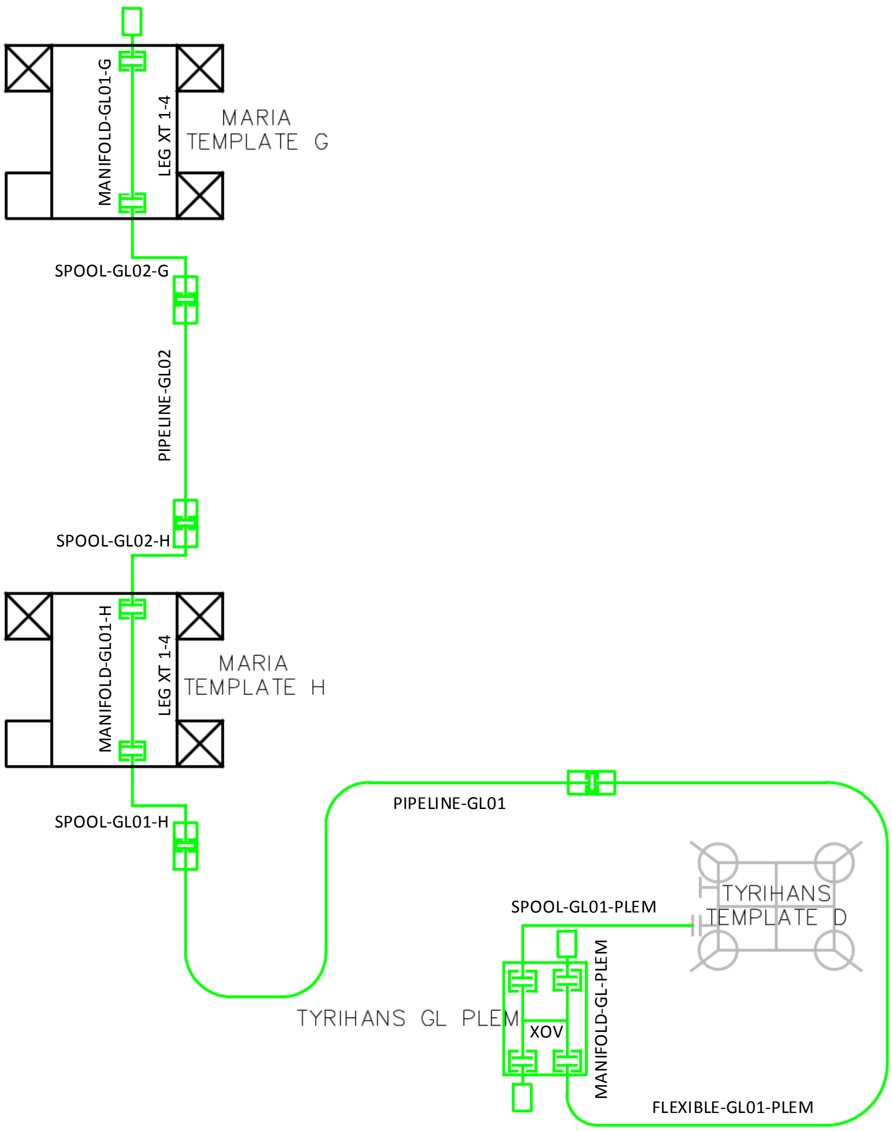


Figure 2.1-2: *Maria gas lift pipeline system components*

Pipeline data

Inner diameter:	0.1317m / 6-inch (main pipeline)
Material spec:	X65 Carbon Steel
Total length:	22 885m (estimated)
Total volume:	318m³ (calculated)
Production fluid:	Åsgaard export gas, used for gas lift purposes

Pipeline parts in these tables are shown in Figure 2.1-2 which is a simplified illustration of the gas lift pipeline system. The gas lift system is segregated into two parts separated by the crossover valve (XOV) at the Tyrihans gas-lift (GL) pipeline end manifold (PLEM).

System	Pipe section	ID [m]	Length [m]	Internal volume [m³]
GL 10"	SPOOL-GL01-PLEM	0.2286	95	3.90
	MANIFOLD-GL-PLEM	0.2286	10	0.41
	LEG XOV	0.1357	2	0.03
SUM			**107**	**4.34**

Table 2.1-1: *Tyrihans to Maria gas lift PLEM system*

System	Pipe section	ID [m]	Length [m]	Internal volume [m³]
GL 6"	MANIFOLD-GL-PLEM	0.1357	10	0.14
	LEG XOV	0.1357	2	0.03
GL 5,5"ID	FLEXIBLE-GL01-PLEM	0.1397	500	7.66
GL 6"	PIPELINE-GL01	0.1317	18830	256.51
GL 6"	SPOOL-GL01-H	0.1357	71	1.03
GL 6"	MANIFOLD-GL01-H	0.1397	40	0.61
GL 2"	LEG XT 1-4	0.0508	20	0.04
GL 6"	SPOOL-GL02-H	0.1357	72	1.04
GL 6"	PIPELINE-GL02	0.1397	3230	49.51
GL 6"	SPOOL-GL02-G	0.1357	72	1.04
GL 6"	MANIFOLD-GL02-G	0.1397	40	0.61
GL 2"	LEG XT 1-4	0.0508	20	0.04
SUM			**22907**	**318.28**

Table 2.1-2: *Maria gas lift system*

2.1.2 Water injection system

The water injection line is running from the Heidrun TLP to the Maria Field with an approach from the north. The main goal of commissioning is to leave this system filled with SRP-water. The SRP-water is sulphate and oxygen reduced to prevent corrosion and scale build-up during production. The SRP-water should preferably contain no gas pockets before pressurization: this is mainly because gas under high pressure may damage the liner in this pipeline system. This is further explained when approaching this system.

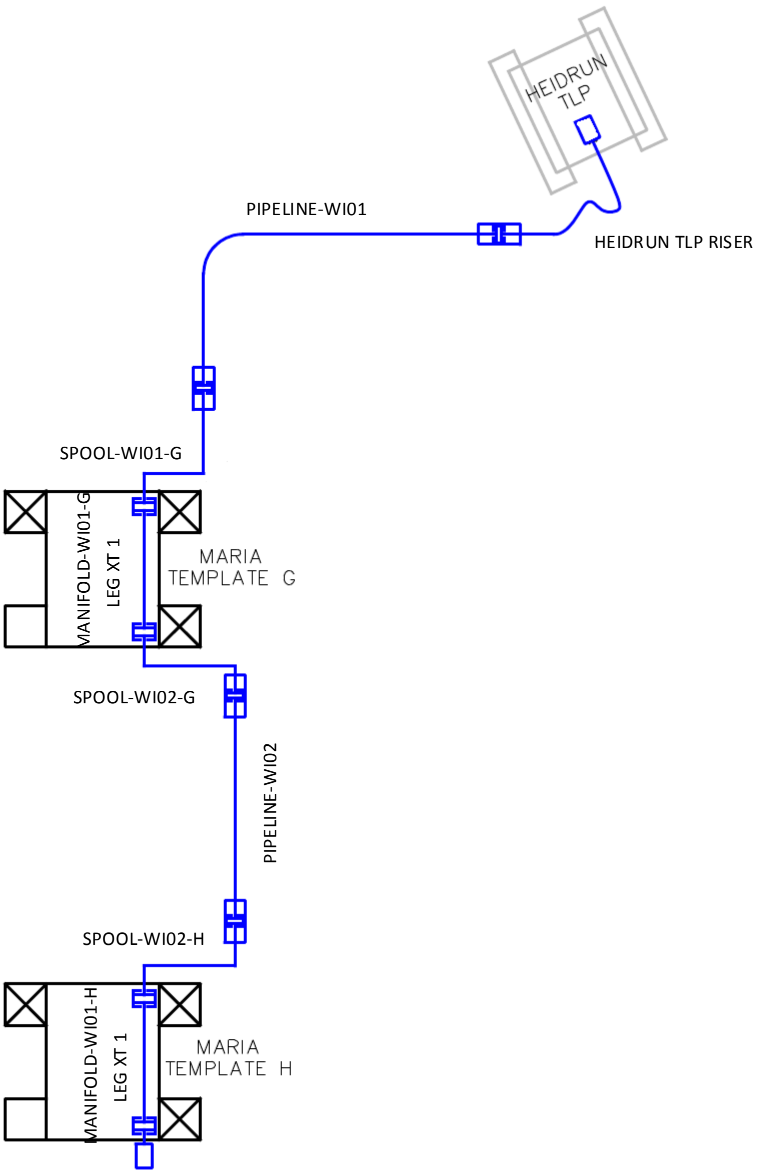


Figure 2.1-3: *Maria water injection pipeline system components*

Pipeline data

Nominal bore:	0.2857m / 12-inch (main pipeline)
Material spec:	Carbon Steel + PE-liner
Total length:	47 325m (estimated)
Total volume:	3 833m³ (calculated)
Production fluid:	Sulphate reduced seawater (water for injection)

Pipeline parts in this table refer to Figure 2.1-3 which is a simplified illustration of the water injection pipeline system.

System	Pipe section	ID [m]	Length [m]	Internal volume [m³]
WI 12"	HEIDRUN TLP RISER	0.2615	500	26.85
WI 12"	PIPELINE-WI01	0.2857	43328	2777.66
WI 10"	SPOOL-WI01-G	0.2415	81	3.71
WI 10"	MANIFOLD-WI01-G	0.2349	40	1.73
WI 3"	LEG XT 1	0.0762	5	0.02
WI 10"	SPOOL-WI02-G	0.2415	76	3.48
WI 12"	PIPELINE-WI02	0.2857	3137	201.11
WI 10"	SPOOL-WI02-H	0.2415	83	3.80
WI 10"	MANIFOLD-WI02-H	0.2349	40	1.73
WI 3"	LEG XT 1-3	0.0762	15	0.07
SUM			**47305**	**3020.17**

Table 2.1-3: *Maria water injection system*

2.1.3 Production system

The production line reaches from Kristin to the Maria Field with an approach from the north. The main production line avoids lifting zones and is tied in using rigid spools. The commissioning of the line will prepare this system for the well start-up. A critical issue is to avoid plugging during start-up especially related to hydrate formation or emulsion of water and oil.

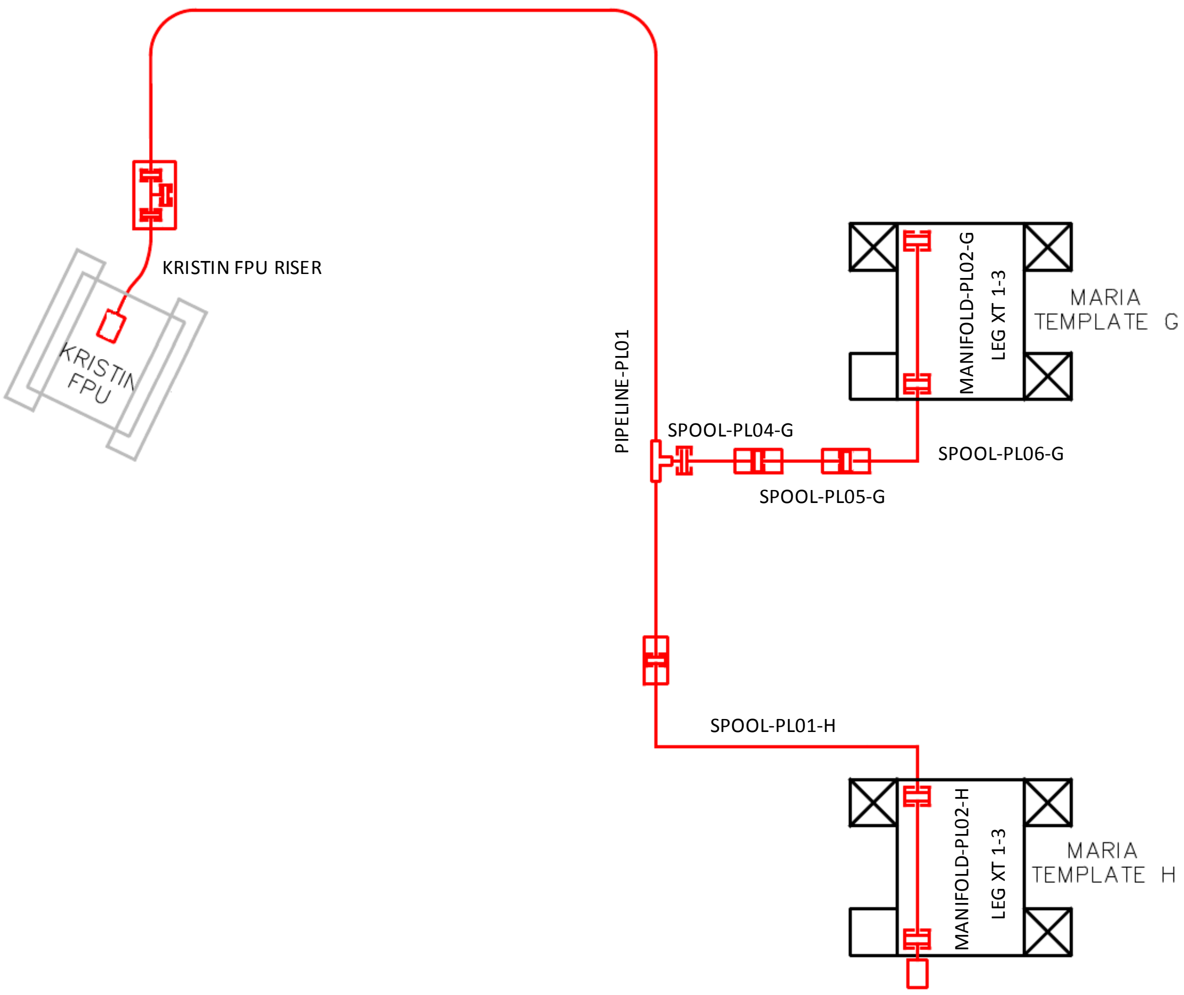


Figure 2.1-4: *Maria production pipeline system components*

Pipeline data

Nominal bore:	0.3052m / 14-inch (main pipeline)
Material spec:	X65, Stainless Steel 316L liner and 625 alloys at each end
Total length:	26 894m (estimated)
Total volume:	1 947m³ (calculated)
Production fluid:	Multiphase crude oil (high temp/high pressure)

Pipeline parts in these tables refer to Figure 2.1-4 which is a simplified illustration of the production pipeline system. The production pipeline system is sorted in two parts separated at the in-line tee (ILT) listed in producing direction from each template.

System	Pipe section	ID [m]	Length [m]	Internal volume [m³]
PL 4"	LEG XT 1-3	0.0762	15	0.07
PL 12"	MANIFOLD-PL02-H	0.2349	40	1.73
PL 12"	SPOOL-PL01-H	0.276	88	5.26
PL 14"	PIPELINE-PL01	0.3052	26022	1903.70
PL 14"	KRISTIN FPU RISER	0.254	500	25.34
SUM			**26665**	**1936.11**

Table 2.1-4: *Production System, Kristin to Maria template H*

System	Pipe section	ID [m]	Length [m]	Internal volume [m³]
PL 4"	LEG XT 1-3	0.0762	15	0.07
PL 12"	MANIFOLD-PL02-H	0.2349	40	1.73
PL 10"	SPOOL-PL06-G	0.2349	68	2.95
PL 10"	SPOOL-PL05-G	0.2349	68	2.95
PL 10"	SPOOL-PL04-G	0.2349	68	2.95
SUM			**259**	**10.64**

Table 2.1-5: *Production System, In-Line Tee to Maria template G*

2.2 Evaluation sheet

After suggestions on a specific issue are found, an evaluation is performed. As a method to decide on the best solution, the evaluation sheet explained in this section was developed. This sheet is an aid designed to combine each point of value related to the area of importance.

Scale of drivers	Value
Important and positive	2
Positive but not critical	1
Neutral	0
Negative but not critical	-1
Negative driver	-2

Table 2.2-1: *Driver criticality*

Pros and cons drivers to each option are valued from -2 to 2 with reference color illustrated. The scale is selected to impact the total evaluation sum in positive or negative direction.

Area of importance	Multiplication factor
Safety to personnel in operation	1.4
Environmental consideration	1.3
Integrity of procedure	1.2
Interface issues to host	1.1
Cost	1

Table 2.2-2: *Area of importance*

Every point evaluated is sorted to the area of importance related to the priority list, [Table 1.3-1, p.9]. Each area is given a multiplication factor to create a difference in priority, based on the area of importance. The multiplication factor scale is set with a difference of 0.1 between areas of importance to make a small difference and still not totally overrule the lower valued areas.

Area of importance	Multiplication factor	Option A:	Value A	Option B:	Value B	Option C:	Value C
Safety to personnel in operation	1.4	High risk	-2	Medium risk	0	Low risk	2
Environmental consideration	1.3	Large spill	-2	Some discharges	-1	Environmental friendly	2
Integrity of procedure	1.2	Safe process procedure	2	Possible issues	-1	Not recommended	-2
Interface issues to host	1.1	Not affected	1	Must cooperate on solution	0	Not accepted by host	-2
Cost	1	High cost	-2	Medium cost	0	Long term cost	-1
Total evaluation sum:			-3.9		-2.5		-0.2

Table 2.2-3: *Example of evaluation sheet*

This matrix is an example, set up only to show the values implemented to calculate the total evaluation sum given by the blue arrows.

$$Total\ evaluation\ sum = \sum (Area\ of\ importance\ multiplication\ factor * Scale\ of\ driver\ value\ \boldsymbol{X})$$

The evaluation sum is compared to the other options for a better total overview of evaluation points. The highest total evaluation sum is evaluated as the best outcome. The evaluation tool gives an overall visual picture of where actions must be implemented to improve each option. The table is not to be used as the final complete decision, but as a tool to help the decision and point out and locate areas for improvements.

2.3 Equipment considered in commissioning procedures

To carry out subsea pipeline commissioning some specially designed equipment must be used. Most of the equipment is specially designed to accommodate each pipeline inner layer and diameter so this equipment is in many cases produced only for a dedicated operation. This section describes the main equipment selected and their required features to accommodate the commissioning procedure.

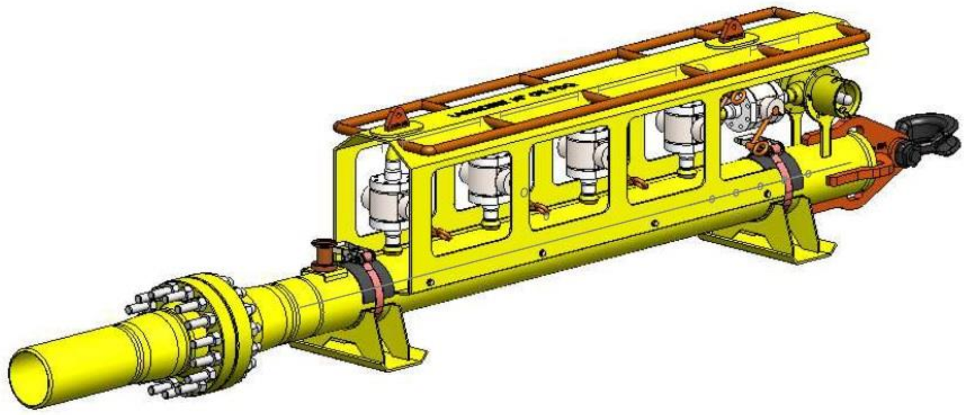


Figure 2.3-1: *Pig launcher/receiver* [5]

Pig launcher/receiver (PLR) is a unit to launch and receive pigs. The PLR is connected to the pipeline end. Fluid for pig displacement is routed behind the launching pig. Valves are operated by ROV to release each pig. The PLR should be of similar size as the pipeline end to the respective system, and subsea PLR should be able to be pre-fitted with the number of pigs required to the commissioning procedure. When the PLR is used as a receiver, all valves are kept open until all pigs have entered the PLR.

Figure 2.3-2: *Cleaning pig* [8]

Cleaning pig usually consists of a set of brushes to loosen pipeline containments from the inside pipeline wall. The most important task of these brushes is to release millscale and residues from welding from the pipeline wall and mix these with the following slug for displacement.

Figure 2.3-3: *Displacement pig* [9]

Displacement pig is designed with flexible wear resistant rubber/plastic to create a slippery plug to displace fluid in a pipeline. A displacement plug may be displaced using either fluid or gas as driving medium.

Figure 2.3-4: *Sealing pig* [10]

Sealing pig is used for pipeline displacement and has the purpose to better seal towards the inside wall of the pipeline. These types of pigs have reference data proven to seal at a higher level than 0,1mm slip around the cups on longer and larger runs then the Maria lines. In the calculations, 0.1mm is used as pig slip thickness, and it is considered as a conservative number where the change in inner diameter in less than ±10% [5, 11, 12].

Figure 2.3-5: *Caliper pig* [13]

Caliper pig is a more complex pig, usually used in the gauging part of pre-commissioning when diameter variations are large. A basic caliper pig is fitted with a set of spring-loaded calipers fitted with rollers for different purposes. Two rollers measure the distance from launch position to record the part of the pipeline measured. A set of rollers records a measurement of the pipeline indentations or out of roundness, all data is stored in the electronic unit inside the body. The sealing cups on this pig have the main purpose of driving the pig and keeping it centralized in the pipeline.

Figure 2.3-6: *Smart pig with tracer*[14]

Gauge pig/Smart pig may also use modern technology such as ultrasonic, electromagnetic flux or radioactive measurement techniques to identify cracks in the pipeline and even external indentation of the pipeline. This is more relevant for inspection use and is often referred to as inspection pigs. In Figure 2.3-6 the pig also carries a transmitter (often radioactive) to detect arrival on the receiving side. Arrival is picked up by a clamp-on receiver or by a measurement device fitted to a remote operated vehicle (ROV). The industry tries to avoid the use of radioactive isotopes because of health safety and environment (HSE) issues, but a good working replacement is yet to be developed on buried pipelines. Ultrasonic or electromagnetic devices do not have the same signal strength at radioactive isotopes

Figure 2.3-7: *Foam pigs* [15]

Foam pig is used where the pipeline has a soft inner liner. The Maria water injection line is designed with a soft polyethylene (PE) inner liner for corrosion prevention. This inner liner restricts the use of regular pigs and for the purpose of cleaning and displacement is a foam type pig should be selected. Foam pigs do not have cups but are molded with a massive foam compound. A danger of the softer foam pigs is dissolvent of the foam material. Small foam pieces may enter branches and valves and may clog the system or disable valves of complete sealing.

Multi diameter pigs come in many different designs; butterfly discs, petal flappers, flexible standards discs, umbrella discs and even foam pigs may be used on lines with different internal diameter.

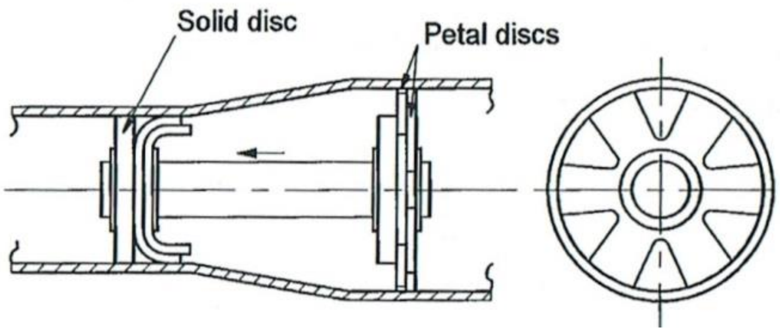


Figure 2.3-8: *Multi diameter pig* [12]

Figure 2.3-8 visualize how a multi-diameter pig works. In this example, a second petal disc made up by several flappers seal the larger diameter section and fold together while entering the smaller section. For the production line, a multi-diameter pig must be used to overcome the inner diameter change. The first section to pig (from Maria template H to the ILT) is the smaller diameter section. The section from ILT to Kristin riser base (RB) is the large diameter section. The vast majority of the intended pigging is performed on the larger inner diameter. Because of this a petal flapper pig is not recommended since the sealing effect between the flappers is limited.

Figure 2.3-9: *Multi diameter pig, special cup with contoured areas* [16]

A multi-diameter pig more suited for the Maria production pipeline is a multi-diameter pig with contoured areas. The mechanics are much similar to the petal flapper disc but instead of flappers the large diameter disc is made flexible by contoured areas that give the large disc flexibility fold together and out depending on the inner diameter. A second smaller disk is also here fitted to seal better on the smallest section of the pipeline. Figure 2.3-9 is a pig designed for a 28 to 42-inch transition related to the Åsgaard gas transport pipeline [16]. The Maria multi-diameter pig will be considerably smaller so the supporting wheels will probably be changed with a supporting disc.

Riser hoses are equipment usually rented to each commissioning operation. In short this is hoses to reach from a vessel to the subsea connection point. The hoses must be fitted with floating elements to reduce tension forces on the hose similar to regular risers. The riser hose properties vary depending on the usage, pressure rating, fluid properties and water depth related to tension. It is not rare to have hoses specially designed to the operation performed. Large water depths or high-pressure ratings may need a hose not available as rental.

Vacuum pump unit is used to evacuate a pipeline as part of the vacuum drying method. This equipment is quite large and power consuming unit. The power source is often optional by open driveshaft at the unit end. The usual power source is a large diesel engine when used on the boat deck of a commissioning vessel. If the vacuum pump unit can be placed onshore or near a powerful electric source, this is a clear advantage. Pipeline evacuation is a very time-consuming operation, and an electric power source is considered more reliable and much better regarding environmental concerns.

Compressor unit is also a portable container unit with the need for a power source. Compressed nitrogen/air for pipeline commissioning is in most cases combined with a drying unit before entering the pipeline.

Pressurized nitrogen tanks are the easiest way to use nitrogen from a commissioning vessel. The nitrogen tanks used for offshore delivery are typical of 8 m^3 and 20m^3 volumes. These tanks contain approximately 5,7m^3 and 16,5m^3 of liquid nitrogen [17]. Besides the nitrogen tanks a heater, mixer and compressor unit must be fitted before use.

Commissioning vessel represents one of the highest costs of subsea commissioning operations. The highest savings to cost is when there are possibilities to shorten down or at best avoid using a commissioning vessel for an operation. Regarding the size of the vessel and the special equipment available on the ship such as moon pool, large lifting capabilities or size to carry large masses the cost vary from 500.000 to 1.000.000 NOK per day.

2.4 Chemicals considered for pipeline commissioning

The following description of chemical products suggested for use in commissioning is sorted by environmental hazard top down. As a guide to the environmental hazards, the environmental classification scheme outlined in the activities regulations is used. This scheme is a list of chemicals that pose little or no risk (PLONOR) to the environment from the Oslo and Paris (OSPAR) convention. "OSPAR is a mechanism of fifteen Governments of the western Europe, together with the European Union, to cooperate and protect the marine environment of the North-East Atlantic." [18]. The scheme contains information on chemicals for use and discharge offshore, and how to rate them after environmental hazard. The Norwegian government has implemented a color coding system by the Norwegian environmental agency and petroleum safety authority. The activities regulation, Section 63 Categorization of chemicals [19]. This is the Norwegian interpretation of the OSPAR directives.

Environmental classification
Substances are tested and generally banned on NCS, their use and release requires an exemption.
Substances are tested and being phased out by substitution.
Substances are tested and the intrinsic properties of yellow-category substances mean that they are biodegradeble.
PLONOR list substances, presumed not to have a significant impact on the environment.

Table 2.4-1: *Environmental classification* [19]

However, care must be taken when differentiating yellow and green-rated products. The color coding does not mean that green classified chemicals are more acceptable to discharge than yellow. The yellow category is tested and proven to have little or acceptable levels of effect on the environment while the green category is presumed to have little or no effect on the environment. The volumes intended for discharge, and the health and safety hazard risks presented by the use of these chemicals must be considered [20].

Wax may be used to coat the inside wall of spools to protect against seawater ingress. There is also the possibility of using wax plugs designed to withstand a certain pressure/temperature before slipping. If used, the effects of such a plug and the ''cannonball effect'' of a slipping plug must also be considered. Most waxes are hydrocarbon products and should not be discharged to sea.

Gel of two types is suggested for use in commissioning. The first is a viscous type of gel injected in front of a displacement pig to improve the sealing effect. The second is a denser type of gel used to pre-fill a spool to prevent seawater contamination. Both these gels are based on glycol and biodegradable, but the gels should not be discharged to sea unless by permit, because of long biodegrading time.

Methanol [21] is excellent as water extractor since it is 100% miscible in water and with this property will better extract water from pores in the pipeline wall. It is also a cheap chemical since it is considered a waste product in several process industries. The cost of methanol is approximated to be around 1 NOK/liter. The chemical is not considered toxic to fish, but discharges to sea have to be according to national authority requirements. Safety regarding methanol handling must be considered since vapor holds a physical health hazard and liquid ingestion are toxic to humans. The fluid is also highly flammable. Methanol is classified as green and listed as PLONOR chemical.

Monoethylene Glycol (MEG) [22] consists of glycol with a purity of around 80%. MEG is much used in the petroleum industry for cleaning and hydrate prevention use. The cost of MEG is estimated to be around 10 NOK/liter. In commissioning MEG is used as slugs between pigs for de-watering. MEG is classified green (PLONOR list) for discharges. This means that potential effects through discharges have not been tested.

Triethylene Glycol (TEG) [23] used for de-watering is typically of 95-99% glycol. TEG is excellent as a de-watering chemical, but also more costly to produce. A cost of 20 NOK/liter must be expected. In commissioning, use of TEG is only used for the lines that require a higher level of de-watering because of the high cost. TEG is classified yellow; this means that it is tested. Compared to MEG and Methanol, TEG is the preferred chemical discharged from an environmental perspective.

Water for injection/SRP-water [24] is produced at the Heidrun TLP and support the Maria field with water for injection. Injection is performed to hold formation pressure for higher production rate and to expand production period. The sulphate reducing package (SRP) removes sulphate ions and salt from seawater to reduce the amount of scaling in the pipeline over time.

Treated seawater
In general this is salt reduced seawater with additives to reduce algae growth (biocide) and corrosion (oxygen scavenger). The biocide additives are very toxic and should be used as little as possible. Some dye is also added in the commissioning phase to show the difference from regular seawater. All additives for use in commissioning must be cleared for discharge to the sea.

Liquid nitrogen [25] used in commissioning heated and compressed before use. Nitrogen is a non-flammable gas and has no restrictions regarding environmental issues. Safety issues are related to the temperature and handling of tanks during transport.

Diesel is suggested to be used in commissioning. Diesel is a hydrocarbon product and environmental wise it is rated as a black product and should not be discharged after use. The advantage of using diesel in commissioning is that the product is not discharged but produced. Diesel will also prevent hydrate formation and holds no danger of mixing with water. The cost of diesel for use in commissioning can be estimated to approximately 5 NOK/liter. Some of this cost will be gained as diesel enter the production, and the displaced diesel will mix with crude production.

2.5 Chemical evaluation

Considering the large volumes intended for de-watering purposes a chemical selection for this purpose is performed by the use of the evaluation sheet.

Area of importance	Multiplication factor	Option A : MEG	Value A	Option C: Methanol	Value C	Option B: TEG	Value B
Safety to personnel in operation	1.4	Toxic with oral intake	-1	Toxic with permanent damage to health	-2	Not toxic	1
Environmental consideration	1.3	PLONOR listed for discharge but not tested	0	PLONOR listed for discharge but not tested	0	Tested to be 100% biodegraded	1
Integrity of procedure	1.2	80% Glycol purity	0	100% miscible in water	1	95-99% Glycol purity	1
Interface issues to host	1.1	Not affected	0	Safety hazard receiving topside	-2	Not affected	0
Cost	1	Medium cost fluid	0	Low cost fluid	1	High cost fluid	-2
Total evaluation sum:			**-1.4**		**-2.8**		**1.9**

Table 2.5-1: *Fluid evaluation for de-watering*

2.5.1 Summary of chemical evaluation

Option A: MEG

MEG is cost saving compared to TEG when large volumes are considered, but it does not hold the same effectivity regarding de-watering. MEG used as de-watering chemical on the production line where water residues are not as critical as on the gas lift line would be a good option based on the cost reduction.

Option B: Methanol

Although methanol has good de-watering properties, the risk posed by toxicity and safety hazard as highly flammable chemical means that one should avoid the use of Methanol as a de-watering liquid.

Option C: TEG

TEG is from an environmental perspective probably the best option regarding discharge to sea as its environmental effects are proven through testing. TEG scores high through integrity because of the good de-watering capabilities. The production of TEG is more demanding than MEG, and because of the high concentration the chemical becomes quite expensive. This chemical should be used on the most critical gas lift pipeline. In production lift gas will not extract water residues but rather mix with H2S and cause a very corrosive environment, because of its efficiency TEG is evaluated as the best chemical to the gas lift pipeline.

2.6 Pipeline pigging

Pipeline pigging is an important part of the commissioning procedure. Pigging is a well-known method in cleaning, gauging and displacement of pipelines. Pigging is also a risk to the system integrity. By using pigs there is always a risk of plugging the pipeline, damage valves, instruments or other vulnerable parts of the system. If a pig partially dissolves during pigging, small parts may cause large problems in capillary sections of the system. As an action to reduce these risks, a pipeline piggability evaluation is performed. Each pipeline is evaluated along the pipeline in the pigging direction to identify possible locations where problems may occur. Piggability is not evaluated related to pre-commissioning pigging since most lines are pigged directly after lay down as a single pipe, and the pigging is performed to identify problems as bending, indentation or out of roundness of the pipeline.

2.6.1 Gas lift system

Pigging is intended from a subsea pig launcher connected to the Tyrihans GL PLEM, to a pig receiver connected to the north side of the Maria template G. Pigs displaced by gas holds a higher risk of large volumes to bypass during a pig slip. This could be limited by the use of a gel slugs in front of each pig. Valves used are intended to be full bore solid ball valves or full bore gate valves to give little resistance during pigging. The first obstacle is the tee connection at the Tyrihans GL PLEM.

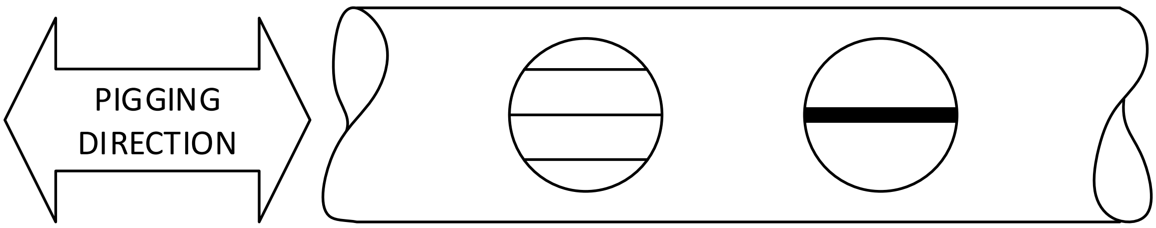


Figure 2.6-1: *Barred tee example*

Tees should be barred to guide pigs past the opening to restrict the possibility of damaging or to get a pig stuck at this position. Three bars mounted horizontally with an individual distance of 50mm [12] should be sufficient. The barring is solved by one larger bar on subsea applications [26]. By increasing the size of the bar sufficient guiding of the pig is provided, and the installation becomes more robust to wear and tear.

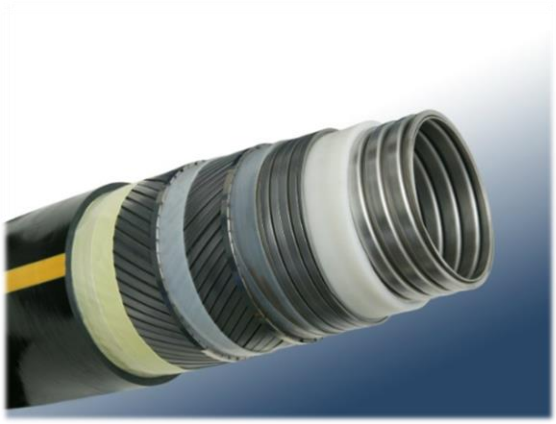


Figure 2.6-2: *Spiral inner layer in a flexible pipe* [27]

The first part of the pipeline after the Tyrihans GL PLEM is a flexible pipe. Bending of the flexible pipe part should (for pigging purposes) be restricted to a bending radius of minimum 30-inch (5xDN) [12] in any direction. The flexible pipeline is not polluted with millscale in the same way as welded rigid pipes and does not need cleaning in the form of cleaning pigs with metal brushes. The inner surface of the flexible pipeline has a spiral inner layer, residues of water may collect in these spirals during pigging. The residues left here should contain as little water as possible.

After the flexible pipe follows a rigid pipeline of ~20km. The rigid pipeline ends in a pipeline end termination (PLET). A rigid spool is used for the tie-in to the manifold at Maria template H. The main purpose of a spool is to reduce mechanical stress on the manifold. The design of tie-in spools is common to have several bends to accommodate stress. Bends in spools should hold the same restriction to bending radius, and multiple bends should at best be avoided without straight sections in between.

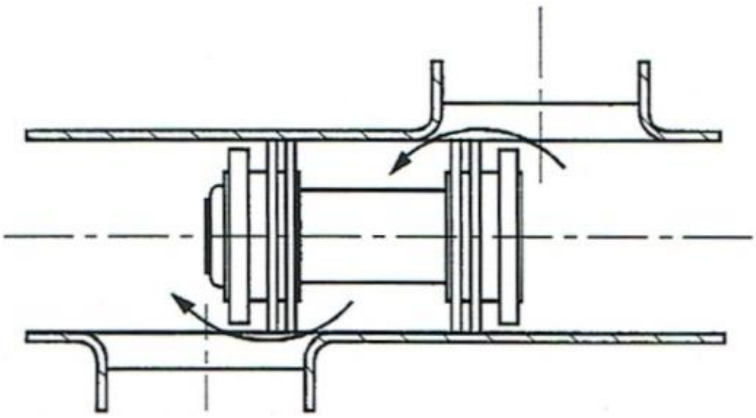


Figure 2.6-3: *Pig stalling between two tees* [12]

A possible obstacle inside each manifold is the possibility of pig stalling between two tees. The branches on the manifold should be tilted towards the main pipe that reduces the probability of pigs to get stuck and also helps to drain these branches. The branches should barred and most importantly designed with a distance larger than 2xDN to avoid pig stalling between two tees.

2.6.2 Water injection system

The displacement direction is intended to be from Heidrun topside to Maria template H and discharge of pipeline intended at the seabed. The riser has a high-quality steel inner layer and is designed to be of the same inner diameter as the pipeline.

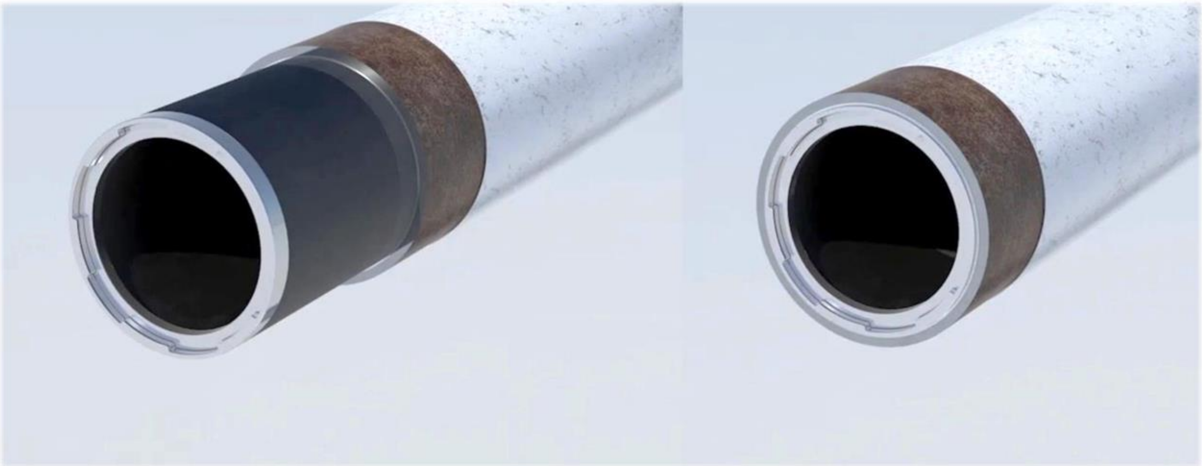


Figure 2.6-4: *Plastic lined steel clad pipe* [28]

The inner layer on the water injection pipeline is of a PE-liner. Construction of this pipeline is performed by pulling a PE-pipe through the steel casing under tension to fit inside with a small clearance. When the tension of the PE-pipe is released, the length will reduce while the diameter expands the PE-pipe will compress towards the inside steel wall function as inside protection liner. The PE-liner will exclude the use of regular pigs since the material used in the cups will damage the PE liner and possibly get stuck. Pigs selected for the purpose of cleaning and displacement is a foam pig. Bending radius of the pipeline is not that critical as regular pigs but a bending radius of minimum 5xDN is used as a guideline on this line. Tees in the manifold should be barred, and distanced with 2xDN. The distance intended to pig must be evaluated by pig supplier in hence of dissolving of the pig by wear and tear.

2.6.3 Production system

The production system is intended to be pigged from the south end of Maria template H past the ILT and to Kristin topside. Bending radius is maximum 5xDN with barred tees in manifolds and distances between branches follows the same guidelines as the other two lines.

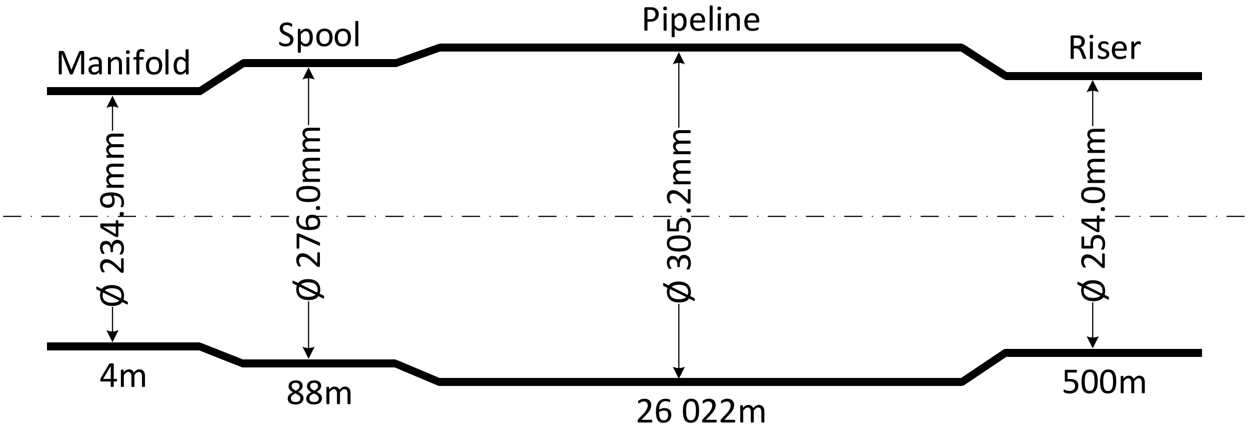


Figure 2.6-5: *Multi diameter section*

The main challenge on the production system is inner diameter differences. This pigging line varies in inner diameter (ID) from 234.9mm in the Manifold to 276.0mm in the spools to 305.2mm at the main production pipeline and 254.0mm in the riser. For this purpose, a special multi-diameter pig must be used Figure 2.3-9. The ID varies with 51.2mm and for multi-diameter pigging, this ID difference should be achievable. The large difference in multi-diameter pigging has been performed on many developments [29] but in most cases pigging from large to small ID is preferred. This pig must fold out and seal on the largest part in the production line and fold back again to enter the riser section.

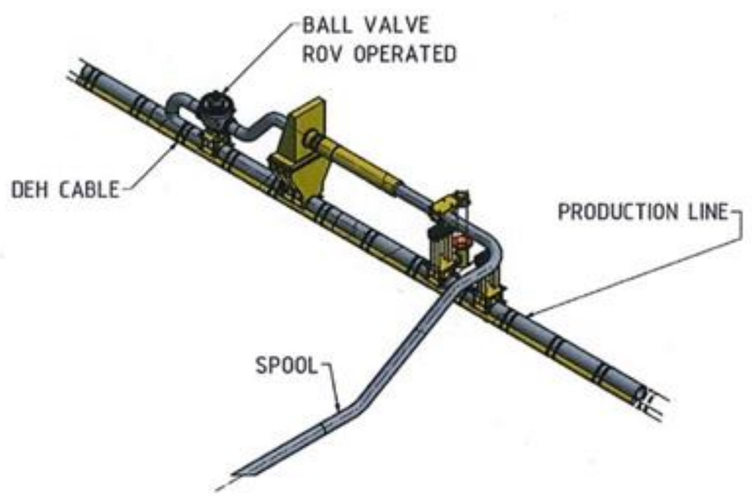


Figure 2.6-6: *In-line tee connection* [30]

The ILT connection is where the spools from Maria template G is connecting to the main pipeline. The spool connection has an ID of 222.7mm while the main pipeline has an ID of

305.2mm. Pigs must be able to pass this point and not get stuck at the in-line tee position towards Maria template G. To best accommodate this connection point to the smaller branch is suggested to be at the top of the production pipeline [30]. This connection should also be barred. The spools from the in-line tee connection to Maria template G is not intended to be pigged.

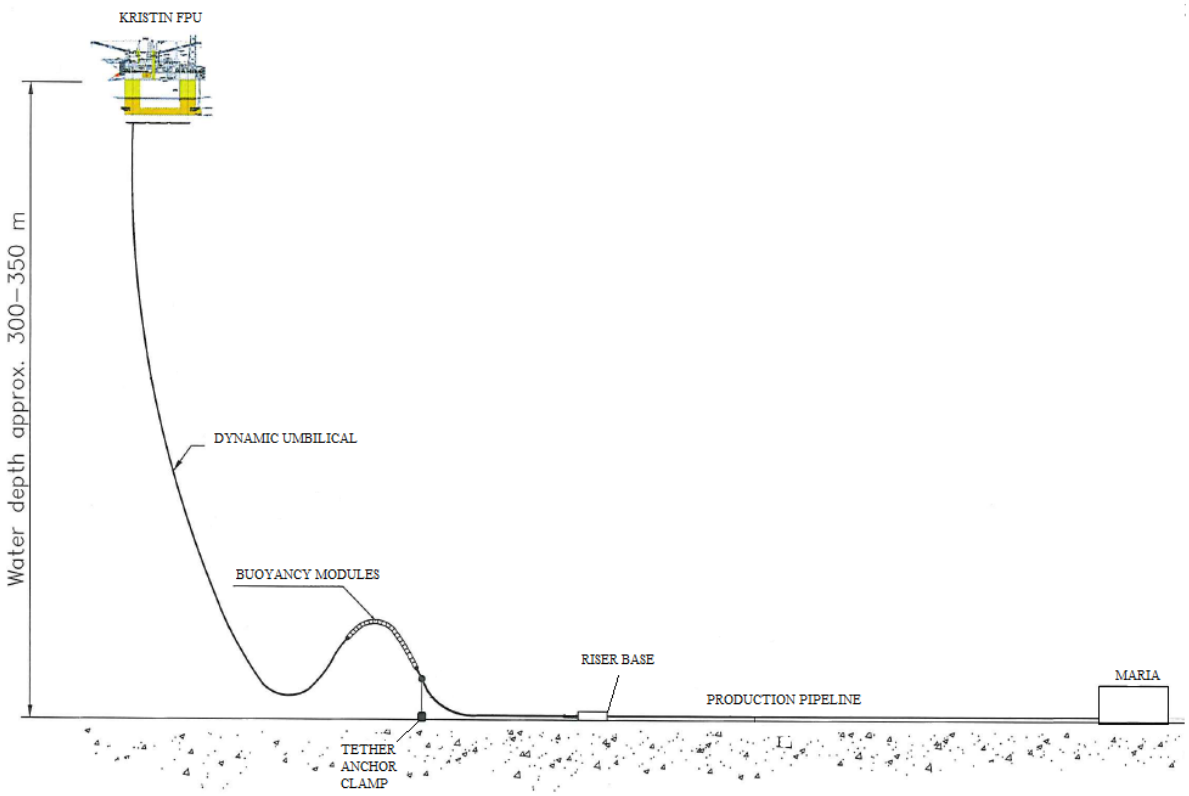


Figure 2.6-7: *Riser illustration Maria to Kristin*

At riser base, the valve should be a full-bore solid ball valve. The riser bend is far larger than 5xDN but the main challenge with pigging up the riser is hydrostatic pressure and gravity. The difference in height will cause a ΔP of at least 30bars, and higher pressure difference must be expected during pigging mainly because of friction. Gas pockets may also slip easier in the riser section since gas will quickly collect behind pigs if present in the propelling fluid. Last obstacle is the bending radius topside. The bending radius in front of the receiver is 3xDN, and this is a point where optimization is possible.

2.7 List of symbols used in illustrations

The offshore vessel used in illustration as commissioning vessel is a Ulstein X-BOW [31]. Standard process and instrument diagram (P&ID) symbols are used in the illustrations. For the simplicity of the illustrations, some new symbols are designed. Ball valves are of a double piston effect (DPE) type and may be regarded as a double barrier. The illustrations must not be regarded as complete P&ID drawing but as a system overview.

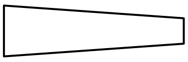
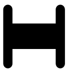
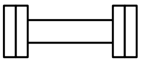
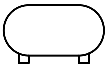
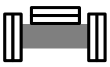
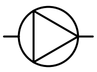
	Intervention vessel
	Pig launcher receiver
	Pig
	Foam pig
	Flange interface/Pressure cap
	Spool
	Open valve
	Closed valve
	Open double piston effect valve
	Closed double piston effect valve
	Separator
	Dryer unit with compressor
	Pressure indication
	In-line tee
	Stabbing point/Connection point
	Pump vacuum/pressure

Table 2.7-1: *List of symbols*

3 GAS LIFT SYSTEM

3.1 Pre-commissioning of the gas lift pipeline

All pipelines are air filled during installation. End caps of the pipeline are combined pressure cap and pig launcher receiver (PLR). The end first laid down is used as the receiving side of the pre-commission pigs. When the pipeline is laid in place on seabed air inside is displaced, the pipeline is cleaned and gauged in one sequence. The pig train usually consists of one cleaning pig, one displacement pig, and the gauging pig. Other pig train configurations may also be necessary depending on the scenario. The cleaning pig is used to brush the inside of the pipeline wall and clean out millscale. Following the cleaning pig is a large slug of treated water to transport residues of loose millscale and other contaminations. Pig number two displaces the contaminated slug and is followed by a gauging pig separated by a smaller slug of treated water. Dye is added to the treated water so that pressure and leak testing may be performed as last part of the pre-commissioning procedure.

Treated water has the purpose of displacing air (most important oxygen) from the pipeline. It should also give a preserving effect to the pipeline. Since the pipeline may lie on the seabed for some time before tie-in, the treated water should be of a composition to prevent marine and algae growth as well as preventing pipeline corrosion. It should also be of environmental friendly properties, so discharge to the sea is optional. Special considerations must be taken in the use of a dye.

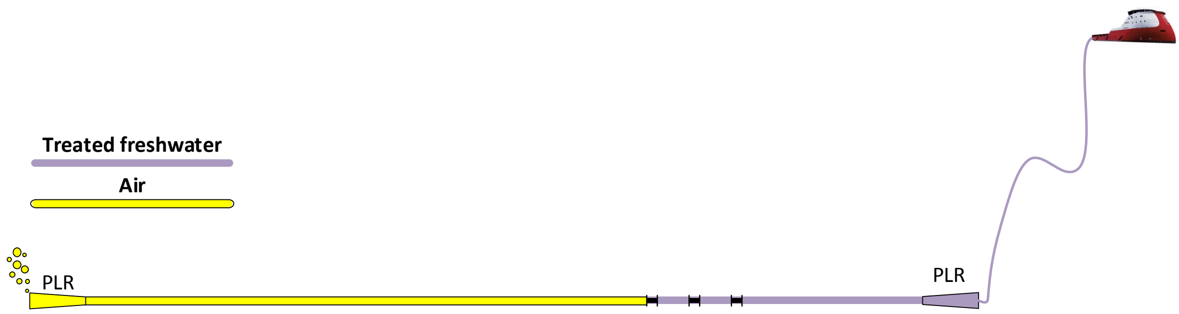


Figure 3.1-1: *Flooding, cleaning and gauging*

Flooding cleaning and gauging illustration above shows the three pigs in a train to clean flood and gauge a new pipeline. PLR at both ends works as pressure concealing caps after use.

Figure 3.1-2: *Air evacuation and pressure testing*

After the arrival of the three pigs, treated water is flushed until air is displaced. Air removal is visually controlled by ROV monitoring air bubbles at the exit point. The pipeline is sealed at the exit end, pressure and leak tested. The pressure is finally reduced to 40bar (10bar above seabed pressure) to restrict seawater ingress. The pipeline is then temporary abandoned.

3.2 Gas lift system battery limits

The gas lift supply to the Maria field is provided from Åsgaard B unit since the Kristin production unit does not have facilities for this. The supply line intended is the gas lift line laid to supply the Tyrihans field from Åsgaard. Physical battery limit of the Wintershall gas lift system is at the end of Tyrihans template D.

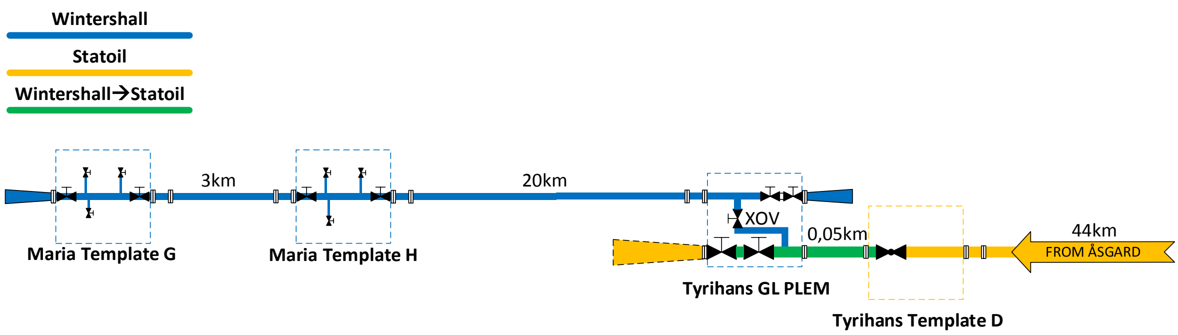


Figure 3.2-1: *Gas lift system overview*

Special consideration has been taken in the tie-in design to maintain piggability from the Åsgaard B unit. The gas lift is to connect to the end of Tyrihans template D. Statoil gas lift line supplying the Tyrihans subsea field is a 10-inch pipeline. This is made possible for pigging from Åsgard B to the end at Tyrihans template D. Statoil have the interest of keeping this line piggable. To solve this Wintershall has selected the option of connection by introducing a Tyrihans GL PLEM (pipeline end manifold). Wintershall then contributes to obtain the piggability from Åsgaard past the Tyrihans Template D.

Regarding commissioning, the gas lift system may be divided into two parts by the XOV at Tyrihans GL PLEM. The Wintershall 6-inch gas lift pipeline is illustrated with blue and Wintershall-Statoil interface 10-inch spool illustrated with green. Each of these pipeline sections will have different challenges during commissioning and operation. Both these pipeline sections on each side of the XOV are prepared before the XOV is combining the systems.

3.3 Consideration to commissioning strategy

Two main challenges have been identified related to the gas lift system commissioning:

1) The de-watering technique of the gas lift system must be evaluated and, a procedure identified. Design basis has set a dryness of -18˚C at 79bar dewpoint since this was the specification set for the Åsgard gas transport pipeline [32].

2) Tie-in connection and pressurizing of the system is the second challenge identified. The tie-in method must be performed safe, and the selected method may also affect the technique of pressurization. Pressurization is related to equalize pressure between the systems and how hydrocarbons should be introduced. Options must be evaluated to fit best the purpose of both Statoil and Wintershall facilities. A critical measure is that operational influence may reach as far as back to the Åsaard B unit if pressure must be reduced in the entire pipeline.

3.4 Gas lift commissioning start-up

The first part of the commissioning explained is common to all procedures. Wherever evaluation of procedure is taken, options are visualized and explained before evaluation.

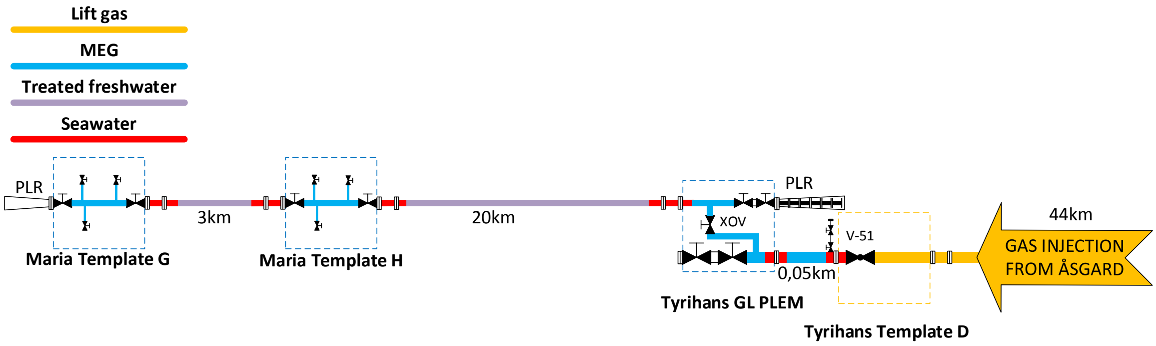


Figure 3.4-1: *Gas lift 6-inch system after tie-in*

Illustration visualizes expected status after completed tie-in. The first part of the commissioning procedure is to be performed on the main Maria pipeline.

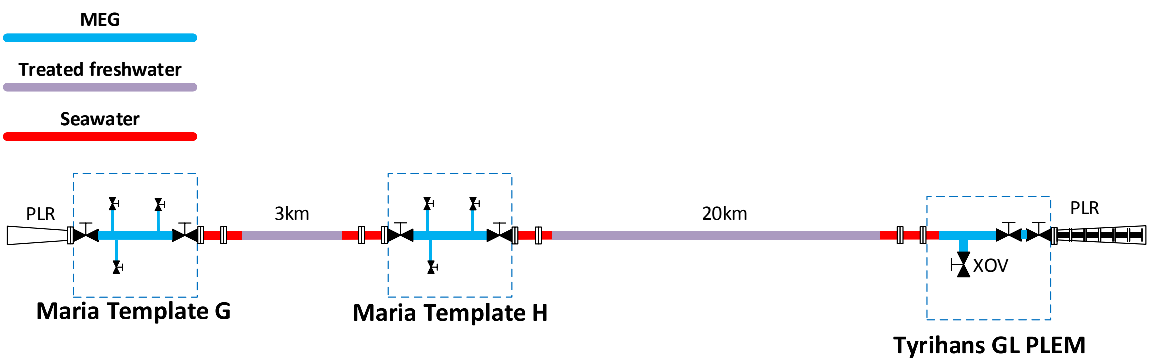


Figure 3.4-2: *Gas lift after tie-in*

The 6-inch gas lift pipeline system consists of two pipes, manifolds at Maria template G and H, three rigid spools and the Tyrihans GL PLEM to the XOV. PLR is attached to each side. Some seawater ingress must be expected at tie-in of spools and pipeline ends. Tyrihans GL PLEM is pre-filled with MEG, all valves are closed and the two open ends fitted with low pressure (LP) end caps to be removed right in front of connecting. This is performed to restrict the amount of seawater ingress at critical parts. Maria manifolds are also MEG filled and closed in by valves and LP caps. The PLR at Tyrihans GL PLEM towards Maria gas lift line is preloaded with displacement pigs.

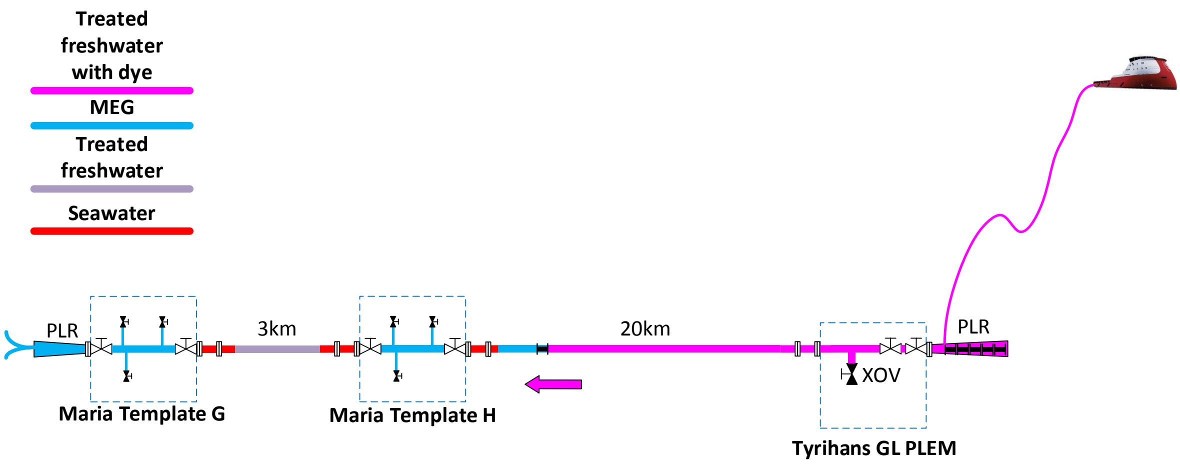


Figure 3.4-3: *Freshwater with dye*

The gas lift line is displaced by the use of one displacement pig propelled by treated water with dye for pressure testing purposes. When dyed water is visual at the PLR at Maria template G, the end valve towards the PLR is closed, and pressure testing performed.

3.5 De-watering of gas lift pipeline

De-watering or drying of the gas lift pipeline is a procedure performed activity to remove water residues to a limit low enough to prevent corrosion of the inside wall of the pipeline. Three options of de-watering are considered and evaluated:

- Option A – Pig-sweep train
- Option B – Air drying
- Option C – Vacuum drying

3.5.1 Option A – Pig-sweep train

The pig-sweep consists of some displacement pigs separated by a fluid who extract water residues. The fluid selected for this task has been selected to be TEG on the gas lift pipeline [2.5.1 Chemical evaluation]. A pig slip calculation is set up to evaluate the number of pigs, the number of slugs and the volume of each slug to sweep the pipeline dry enough to meet requirements of dryness. Input data is collected from design basis and the bypass thickness based on experiences both from online published papers and IKM-Testing long time experiences with de-watering pigging [4, 7, 16, 29, 33]

Input data	Symbol	Value	Unit
Inner diameter	d	0.1317	m
Pig bypass thickness	t	0.0001	m
Pipe length	l	22865	m
Slug volume	Vs	4.9	m^3
RFO pressure	Ppig	4000000	Pa
Pressure atmosphere	Patm	100000	Pa
Density water	ρw	1000	kg/m^3
Pipeline volume	V	311.48	m^3
Pipeline inside area	Ai	9460.34	m^2

Table 3.5-1: *Input data for pig slip calculation*

The selected slug volume of 4,9m³ relates to calculated water residues below acceptance criteria after use of four slugs. The calculation has been performed by calculation the total bypass for the entire run and assumed the water content in the next slug to be of a content similar to the one calculated after a full sweep. By this, the calculation is considered conservative since each slug starts with close to no water residues. Plotting table and a larger graph are attached [Appendix A].

$$Bypass\ volume = V_{bx} = \frac{\pi}{4} * (d^2 - (d-t)^2) * l$$

$$Water\ content\ in\ slug = W_{cont\ X} = \frac{V_{bypass} * W_{content}}{V_{MEG} + V_{bypass}}$$

$$Residual\ water = R_{wx} = \frac{V_{water\ residue} * \rho_w * P_{atm}}{V * P_{pig}}$$

Calculation	Symbol	Value	Unit
Bypass volume of the first pig	Vb1	0.4728	m^3
Water content in MEG slug 1	Wcont1	0.0965	%
∑Residual water in pipeline	Rw1	37.9507	g/m^3
Water volume in MEG slug 2	Vb2	0.0456	m^3
Water content in MEG slug 2	Wcont2	0.0093	%
∑Residual water in pipeline	Rw2	3.6621	g/m^3
Water volume in MEG slug 3	Vb3	0.0044	m^3
Water content in MEG slug 3	Wcont3	0.0009	%
∑Residual water in pipeline	Rw3	0.3534	g/m^3
Water volume in MEG slug 4	Vb4	0.0004	m^3
Water content in MEG slug 4	Wcont4	0.0001	%
∑Residual water in pipeline	Rw4	0.0341	g/m^3

Table 3.5-2: *Calculation on selected slug volume*

Colours in Table 3.5-2 refer to colours used in Figure 3.5-1. Pipeline dryness with a dewpoint of -18˚C (Åsgard specification) are similar to a water residue of 0.0374g/Sm^3 (saturated air at -18˚C holds this density) [34].

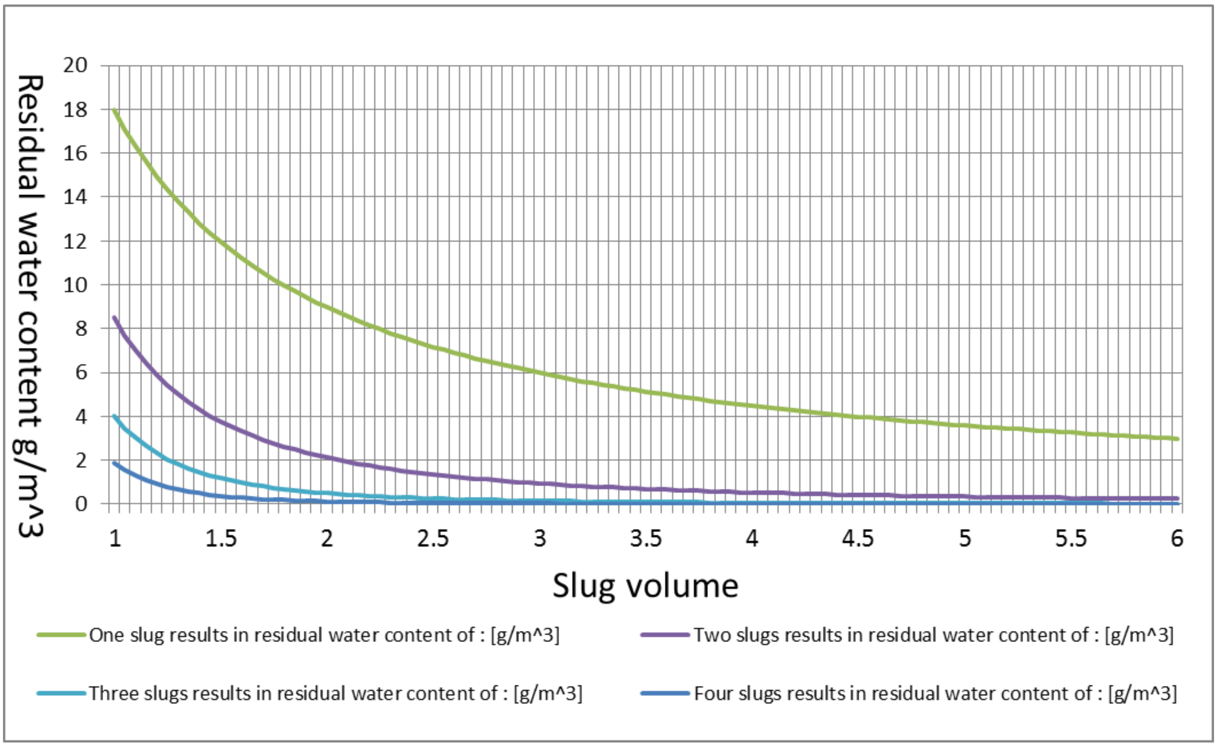


Figure 3.5-1: *Slug volume plotting*

Calculations recommend either the use of four slugs of 2.8m³ each or three slugs of 4.9m³ each (Appendix A). To reduce the volume of slug liquid four slugs is selected and add up to a total volume of total volume of 11.2m³. To perform this, the PLR's must be able to hold a total of 6 displacement pigs. The MEG slug in front of the pig-sweep train from the pre-filled GL PLEM is not considered in the calculation since this quickly will be mixed with water in the lack of a separation pig.

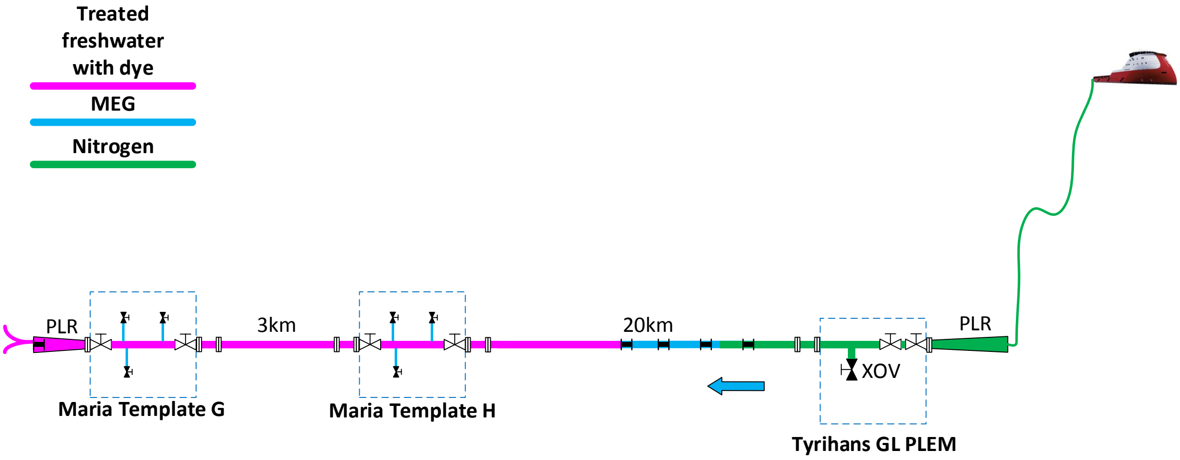


Figure 3.5-2: *Pig-sweep with MEG slugs*

The pig-sweep train is propelled by Nitrogen supplied from a vessel. The Nitrogen should be filled in a rate to hold minimum 40bar. The velocity of the pig train should be maintained constant at 0,4-0,5m/s for best sweeping efficiency [5]. This is controlled by a flowmeter at the discharge point keeping the flow in the range 22-28m³/h. The volume of this pipe section is calculated to be ~318m³ without the hose volume at outlet connection. The time estimate of the pig-sweep alone is estimated to be around 12 hours.

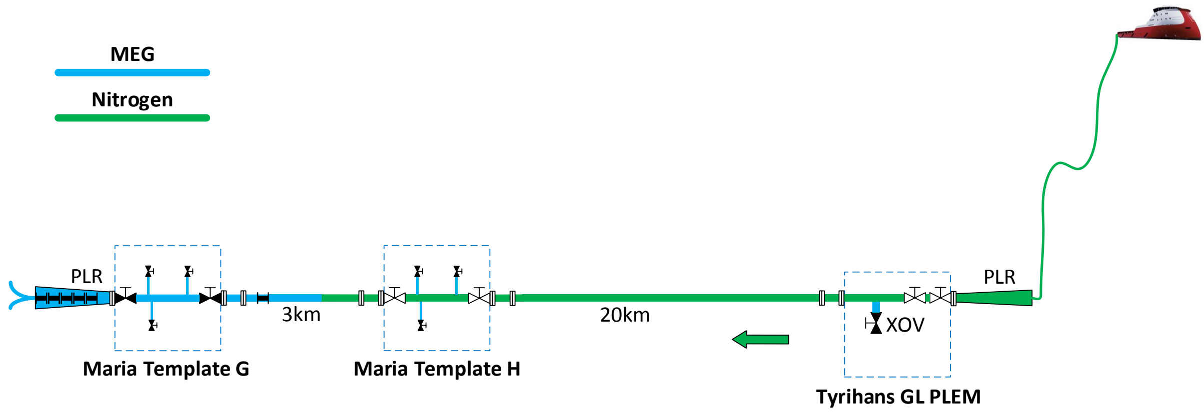


Figure 3.5-3: *MEG residue purging*

It is expected that it will be necessary to reduce the valve opening at the outlet during operation to keep a constant velocity to the pig sweep train. If a valve with constant opening is used, the pig train will increase the velocity as friction is reduced by the reduction of fluid in the pipeline. MEG residues from lines towards production trees will drain into the main pipeline when liquid is replaced by Nitrogen. This amount in addition to the residue film left on the pipeline wall after the last displacement pig is estimated to add up to a total of ~0,5m³ MEG and ~0,02m³ water evenly left in the pipeline after drying.

3.5.2 Option B – Air drying

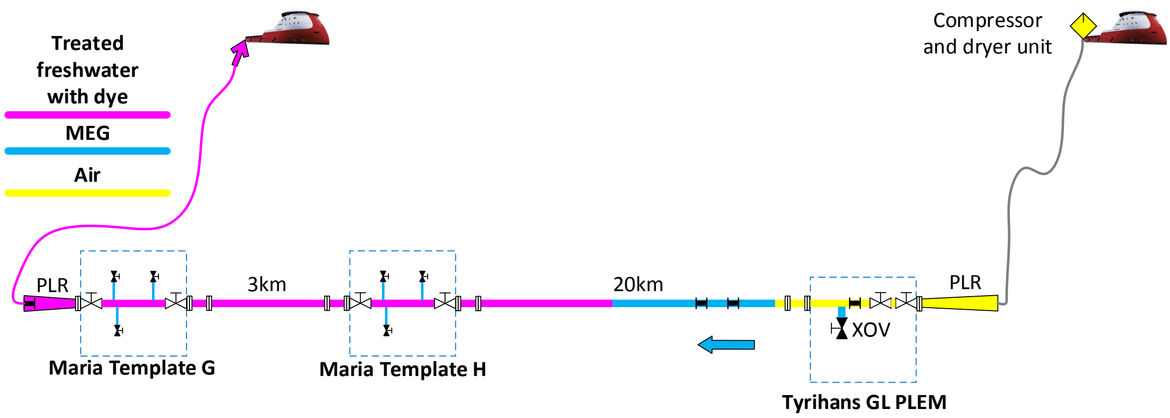


Figure 3.5-4: *Pig-sweep with MEG and air slugs*

Air drying is performed by a small pig train separated with slugs of MEG. Then a slug of compressed air is introduced before the last pig is sent. The idea of an air gap slug in front of the last slug is to let the smaller connections drain into the main pipeline and be swept out with the last pig. The air used is dried to a level of dryness of approximate dewpoint at -60˚C [35].

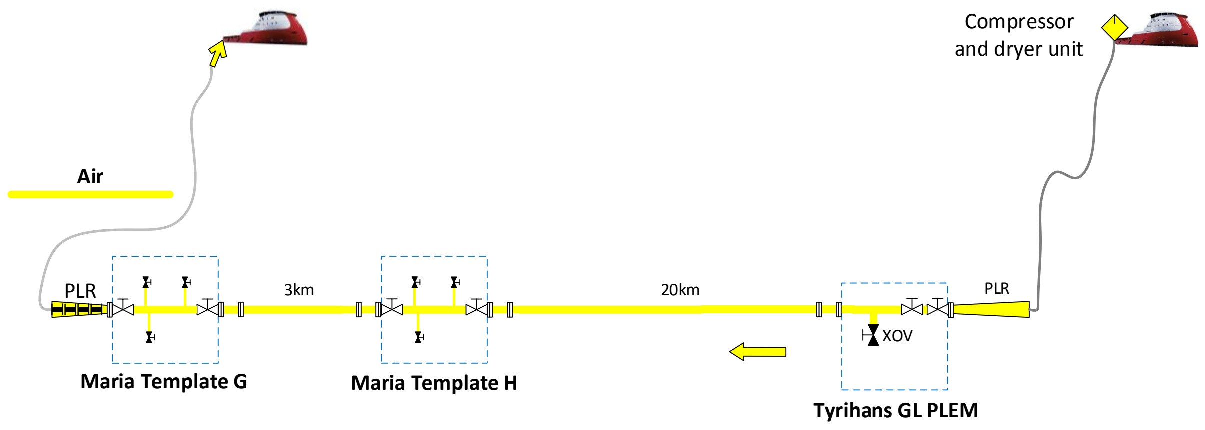


Figure 3.5-5: *Drying*

At the receiving side by Maria template G, a vessel is connected to the outlet to control pigging speed and receive displaced liquid. Dryness of the system is measured by a hydrometer at the receiving vessel to confirm pipeline dryness.

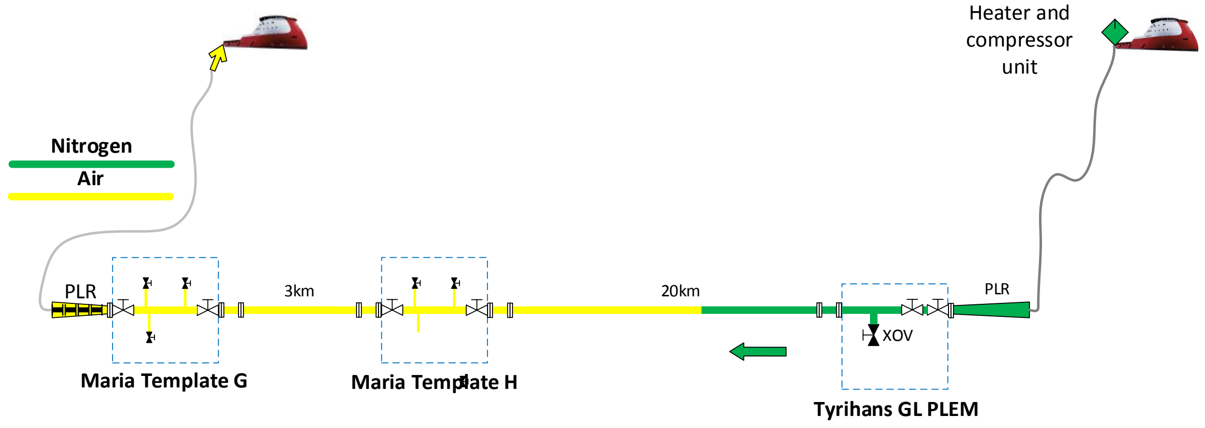


Figure 3.5-6: *Nitrogen displacement*

As the final stage, air has to be displaced with nitrogen to reduce the amount of Oxygen in the pipeline. Oxygen is both corrosive and causes explosive danger mixed with hydrocarbons, this is why the air has to be displaced.

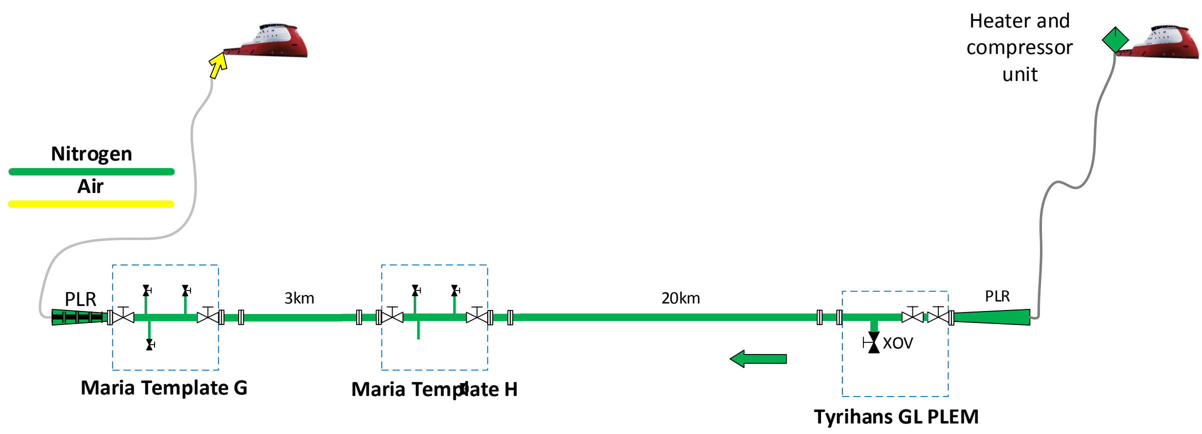


Figure 3.5-7: *Air displaced by Nitrogen*

It is critical that the introduced Nitrogen holds a lower dew point than measured in the pipeline.

3.5.3 Option C – Vacuum drying

The vacuum drying procedure consists of three steps, evacuation, evaporation and final drying. Evacuation is to reach a limit to ensure the level of water residues to be under considered corrosion risk level. In general corrosion-formation is considered at relative humidity (R.H.) level above 30%. But in the presence of millscale, corrosion may occur at a level of 20% R.H. [36]. By this, the pipeline should be dried to a target dew point below 20% R.H. in correlation to the coldest part of the system. Temperatures as low as 0˚C during winter is set as lowest temperature expected. Saturated vapour pressure (SVP) at 0.01˚C is 0.6113kPa [37]. The vacuum level required to reach 20% level of R.H. is a water vapor pressure (WVP) of 0.12kPa.

$$WVP = SVP * R.H. = 0.6113kPa * 0.20 \approx 0.12kPa$$

20% R.H. at 0.12kPa correspond to a dewpoint of -18˚C. It is normal under this procedure to continue the evacuation to a level of dewpoint ~10˚C lower than design basis as a conservative measure.

After a vacuum of this level is reached, evaporation starts. The time for the evaporation of the residues to completely transfer liquid water to water vapor is depending on the amount of water residues in the system. The ambient temperature and the vacuum equipment used will affect the time consumption.

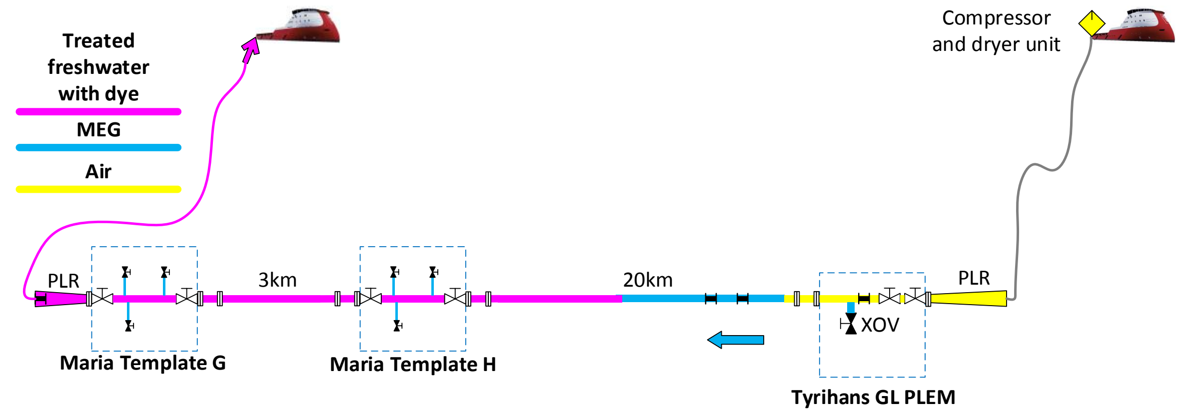


***Figure 3.5-8:** Liquid displacement*

The first part of this procedure starts with a pig-sweep. Treated water, is displaced by a pig train with MEG separated slugs, the train is propelled by compressed air.

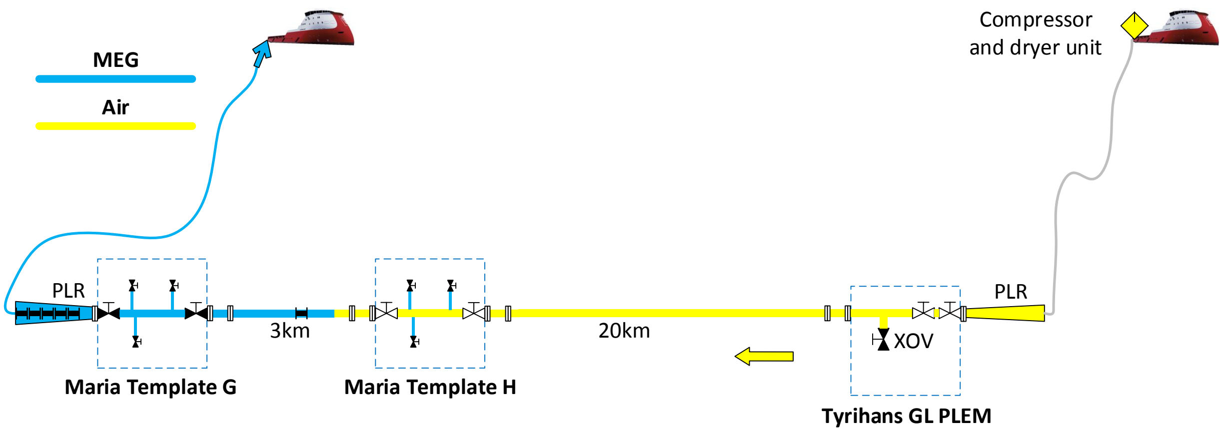


***Figure 3.5-9:** MEG displacement*

After the pig train has reached Maria template G, air is purged until the major MEG residues are being displaced to the receiving vessel.

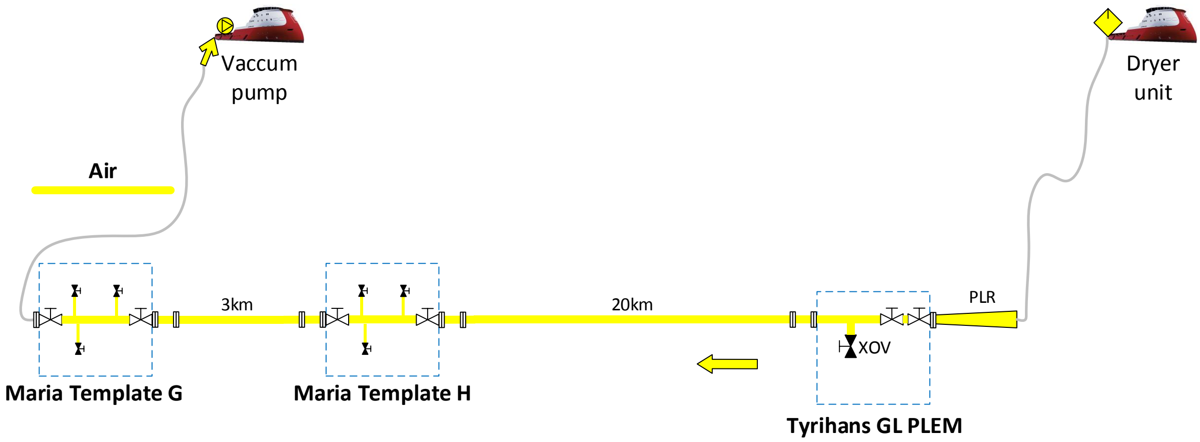


Figure 3.5-10: *Evacuation and evaporation*

Evacuation is performed by a vacuum pump at the receiving vessel. Valves and pipeline connections must be vacuum resistant including the flexible spool to the Tyrihans GL PLEM. Pressure in the pipeline is first reduced to atmospheric pressure, and the vacuum pump is initiated to decrease further pressure to the calculated level. At a point during evacuation pressure, the pressure reduction rate will decrease noticeable. This confirms that the pressure at this point is the vapor pressure. Once this level is reached, evaporation phase begins. The water will evaporate and expand, and this is the cause of the reduced pressure reduction rate. Pressure reduction and evaporation must continue to 0.12KPa has been reached. Once this limit has been reached a test is performed to make sure all the residues have evaporated. The pipeline is isolated for 12 hours and pressure noted. If the pressure remains constant evaporation is complete.

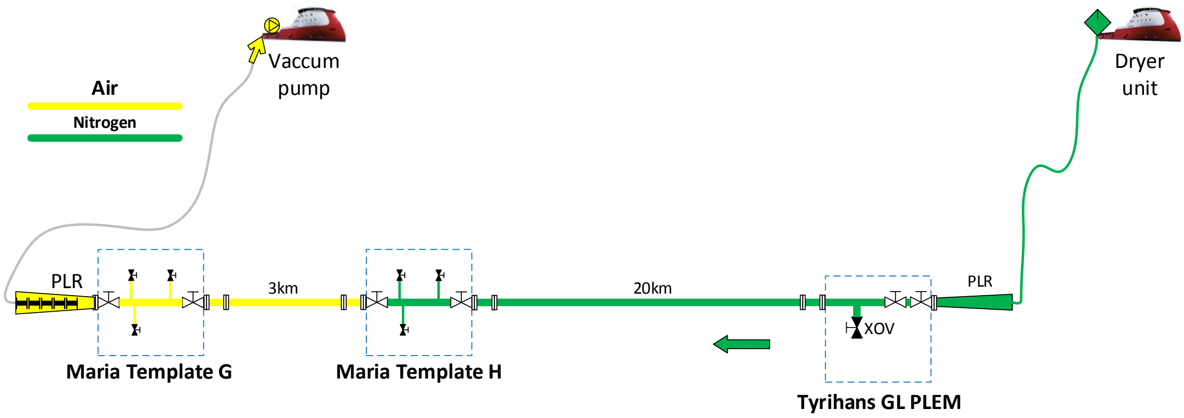


Figure 3.5-11: *Final drying and Nitrogen purging*

When the water residues have evaporated, the water vapor in the pipeline must be removed. This is performed in the final step of vacuum drying by further decreasing pressure and draw out the vapor by the vacuum pump. Dry Nitrogen is injected at the end opposite from the vacuum unit at a rate as low as the pressure never rises above 0.12kPa.

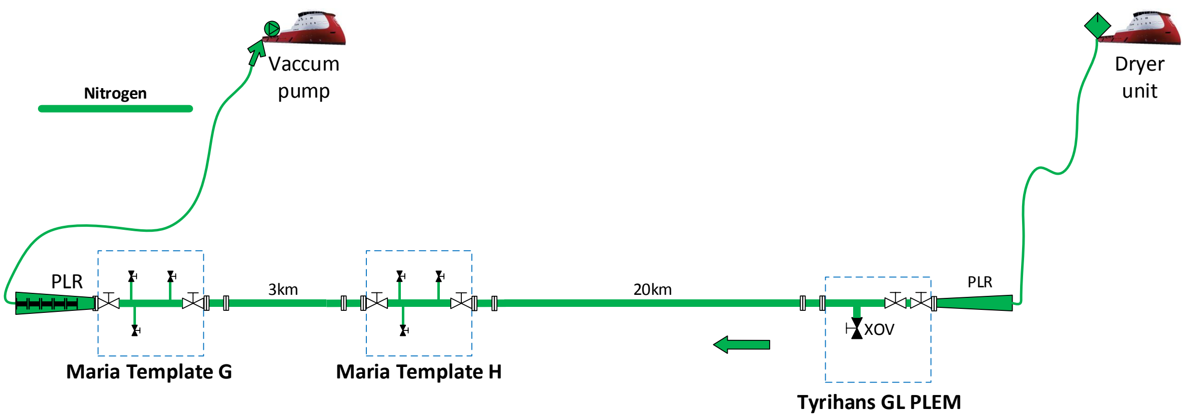


Figure 3.5-12: *Final drying and Nitrogen purging*

After the volume of the pipeline with a safety margin has been ejected, Nitrogen is purged by a compressor unit until a dewpoint of -18˚C is measured. Then the system is pressurized to above hydrostatic pressure (40bar).

3.6 Drying method evaluation of the gas lift system

Area of importance	Multiplication factor	Option A : Pig sweep	Driver value A	Option B: Air drying	Driver value B	Option C: Vacuum drying	Driver value C
Safety to personnel in operation	**1.4**	Medium equipment handling on vessel	0	Much equipment handling on vessel	-1	Much equipment handling on vessel	-1
Environmental consideration	1.3	MEG and Nitrogen discharges	-1	MEG and Nitrogen discharges	0	MEG and Nitrogen discharges	0
Integrity of procedure	1.2	Field proven	2	Field proven	2	Field proven	2
Pipe dryness	1.2	Calculated with uncertainty and MEG residues left in pipeline	-2	Measured	1	Excellent (Measured and will extract manifold legs)	2
Startup considerations	1.2	Large MEG residues left in the pipeline	-2	Oxygen must be displaced after drying	-1	All parts must be vacuum resistant	-1
Interface issues to host	1.1	Not affected	0	Not affected	0	Not affected	0
MEG usage	1.0	High	-1	Medium	1	Low	2
Nitrogen usage	1.0	Low	-1	Low	1	High	-1
Pig sweep before drying	1.0	Sweep and drying perfomed together	2	Yes	-1	Yes	-1
Mob/Demob	1.0	Some higher MEG supply	1	Large air dryer and compressor unit needed	-1	Air dryer, compressor and vacuum pumps	-2
Time/Cost estimate of drying operation	1.0	24h pig train duration, total operation estimated to 48h/Low cost	2	Over one week/High cost	-2	Approximated to one week/High cost	-2
Total evaluation sum:			**-0.7**		**-1**		**-1.8**

Table 3.6-1: *Evaluation sheet of drying technique*

3.6.1 Summary of evaluation

Option A: Pig-sweep
A fast and effective method of reducing the water content, but the residues of MEG left in the pipeline is considerable. The critical point is that the dryness never is measured but only calculated. The only measure of dryness is the concentration of water in the last slug. Nitrogen as propelled gas is an effective technique to reduce oxygen content.

Option B: Air drying
The size of the pipeline results in a low directly displacement effect of water residues. The water residues have to evaporate before it effectively is displaced. The effectiveness of air drying highly depends on an effective pig-sweep. A last pig displaced by an air gap is effective to drain branches to the main pipeline. A negative driver to the method is the introduced oxygen.

Option C: Vacuum drying
This option is the one that is guaranteed to dry completely the pipeline and leave it free of residues. But the operation is complicated and very time consuming. To reach the wanted vacuum pressure, evaporate and displace may take very long time. Reference operations of similar size suggest 1-2 weeks of operation time and is not a method of priority [5].

3.7 Identified points of optimization and conclusion

The evaluation Table 3.6-1 suggests pig sweeping as the most suitable method considering the total evaluation sum. The system is well suited for pigging operations since the changes in inner diameter is kept at a minimum. The fact that no riser is to be displaced is a pigging advantage. Branches connected to the system are few, and they are almost all gathered at the end of the pigging route. As a base case to the optimization, a pig-sweep is suggested.

As calculations identify, the best sweep is achieved by the highest number of slugs and not by a large volume of each slug. But by reducing the pig train with one pig this may be compensated by increasing the slug volume. In this case by reducing the number of slugs to three and increasing the volume of each slug to at least 4,9m^3, the water residues after three slugs is calculated to be similar.

In the first two slugs, water content calculations are considered conservative since they are calculated with water content similar to the approximated end content after pigging. Even so the water content in the third slug may not be as effective as the first two, since the amount now is so small that water in the pores of the metal pipeline wall not will mix as efficient as the first residues [29]. To compensate this and for optimization the fourth displacement pig to separate slug two and three should also be fitted with brushes to mix better the outer layer of water residues.

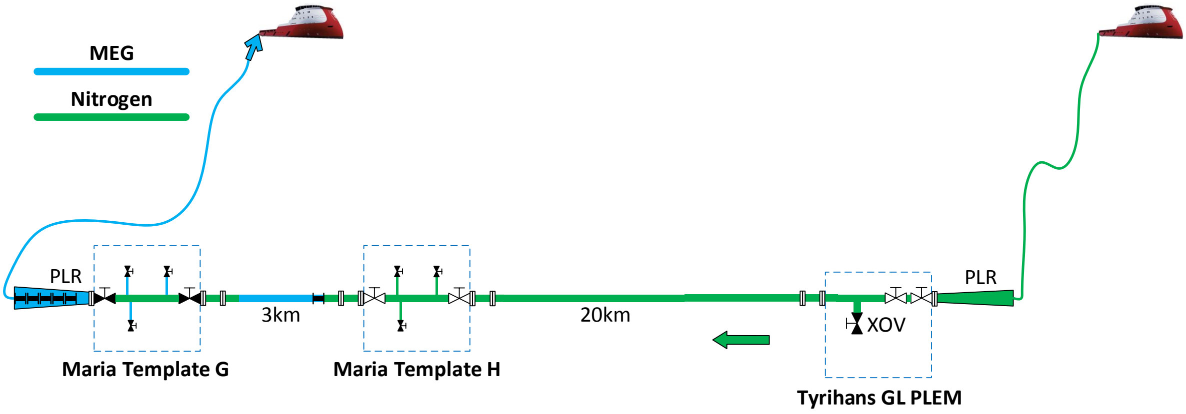


Figure 3.7-1: *Last pig displaced with Nitrogen*

By adopting the technique from air drying by displacing the last pig with gas, the residues left after pig sweeping will be reduced. A calculation is performed to find the minimum volume of such a Nitrogen slug.

3.7.1 Nitrogen slug calculation

This calculation is performed to find the minimum amount of nitrogen recommended to use as a displacement of a last pig to sweep the residues after the primary de-watering train. This is performed to let residues drain from the connection between manifold and XT (referred to as XT leg). The intention is that the total fluid volume collected in this nitrogen slug does not reach the level of the XT leg connection, so these legs have the possibility to drain completely. These legs are of smaller ID and connected to each side of the manifold. The lowest connection point is assumed to be at 30% height level of the ID.

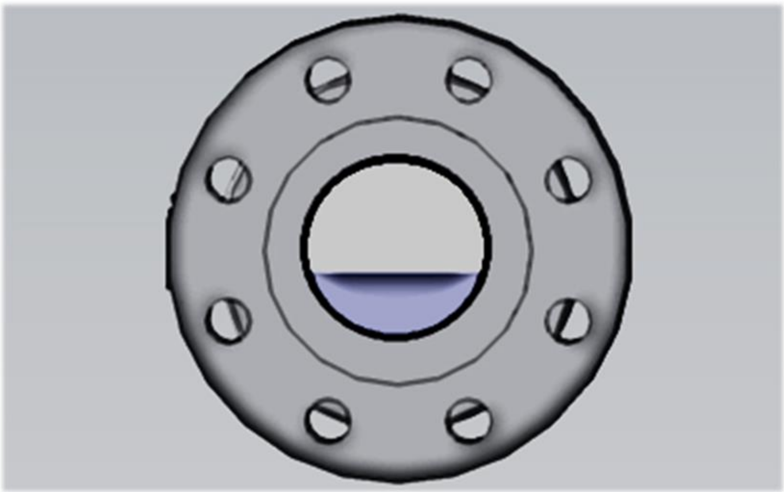


Figure 3.7-2: *Maximum pipeline filling*

Maximum pipeline filling in the intended nitrogen slug should not increase the level of 30% filling height.

Input data	Symbol	Value	Unit
Inner diameter	d	0.1317	m
Inner radius	r	0.06585	m
Lowest branch connection	y	0.03951	m
Expected residues after the de-watering train		0.473	m³
Expected residues in branches		0.110	m³
Sum of residues	Vres	0.583	m³
Expected maximum pigging pressure	Ppig	4000000	Pa
Pressure atmosphere	Patm	100000	Pa

Table 3.7-1: *Nitrogen slug calculation input*

Input data is collected from the pig slip calculation and reference [7, 33].

$$A_{(x)} = 2\int_{0}^{y} \sqrt{r^2 - (r-y)^2}\, dy$$

Volume calculation is performed by integrating the cross section area from the bottom of the pipeline with limits from zero to the lowest branch connection. This calculates the cross section area of the partially filled pipe.

$$A_{(y)} = \frac{2 * r^2 * \sqrt{y} * \sqrt{2 * r - y} * tan^{-1}\left(\frac{\sqrt{y}}{\sqrt{2 * r - y}}\right) - y * (2 * r^2 - 3 * r * y + y^2)}{\sqrt{y * (2r - y)}} + constant$$

This formula is derived from the integral and used to calculate the cross section area.

$$l = \frac{V_{res}}{A_{cs}}$$

Using the calculated cross section area the minimum length of the slug to achieve a liquid level below the branch connection can be found.

$$V_{section} = \frac{\pi}{4} * d^2 * l$$

The total volume of the pipeline section is then found using this length.

$$N2_{volume} = V_s * \frac{P_{pig}}{P_{atm}}$$

The nitrogen volume measured in Sm³ to achieve this volume under pressure is calculated with the estimated pressure needed to drive and displace and the complete pig train.

Calculations	Symbol	Value	Unit
Cross section area of filling to branch lower point	Acs	0.0034	m^2
Nitrogen slug length	l	169.6	m
Pipeline cross section	A	0.0136	m^2
Total volume of Nitrogen slug length	Vs	2.3	m^3
Volume of Nitrogen needed in slug	N2vol	92.4	Sm^3

Table 3.7-2: *Nitrogen slug calculations*

3.7.2 Calculation summary

After the three slugs has swept, residues of ~0.5m³ (Appendix A) is left in the pipeline as a thin coating on the inner pipeline wall. Branches along the pipeline will also drain out to the main pipeline, and this is estimated to be in total 0.110m³. The drain point is estimated to be fitted at least 40% raised from the bottom on the pipeline side to allow a last pig to sweep out as much of the residues as possible. The residues is intended to be swept out by a final fifth displacement pig separated from the fourth pig by 92.4Sm³ of nitrogen. This amount will separate the last pig with 169.6 meters and allow the residues to drain and be swept out in the lower section of the pipeline. Even after this some residues must be expected, so after all pigs are received dry Nitrogen must be purged to a measured level of dryness is achieved before the pipeline end is sealed.

3.8 Tie-in of gas lift system to Tyrihans template D

The tie-in operation is not a part of the commissioning. But because of the importance of this operation and the impact this may have on commissioning it is included and discussed.

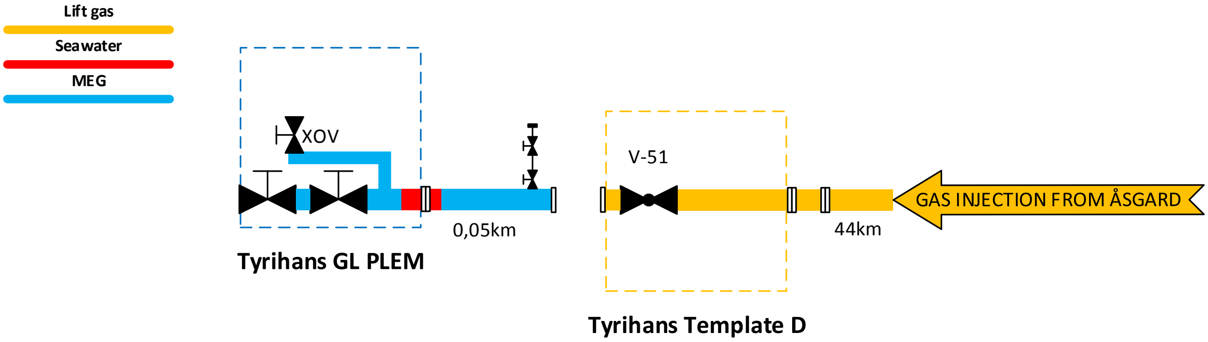


Figure 3.8-1: *Establish connection towards Tyrihans*

At this point, the 6-inch pipeline is considered dry and pressurized as minimum above hydrostatic pressure with Nitrogen. The 10-inch part of the GL PLEM and the spool between Tyrihans GL PLEM and Tyrihans template D is pre-filled with MEG and fitted with low-pressure LP end caps to avoid seawater ingress. The 10-inch spool is the last and critical piece of tie-in on the gas lift system.

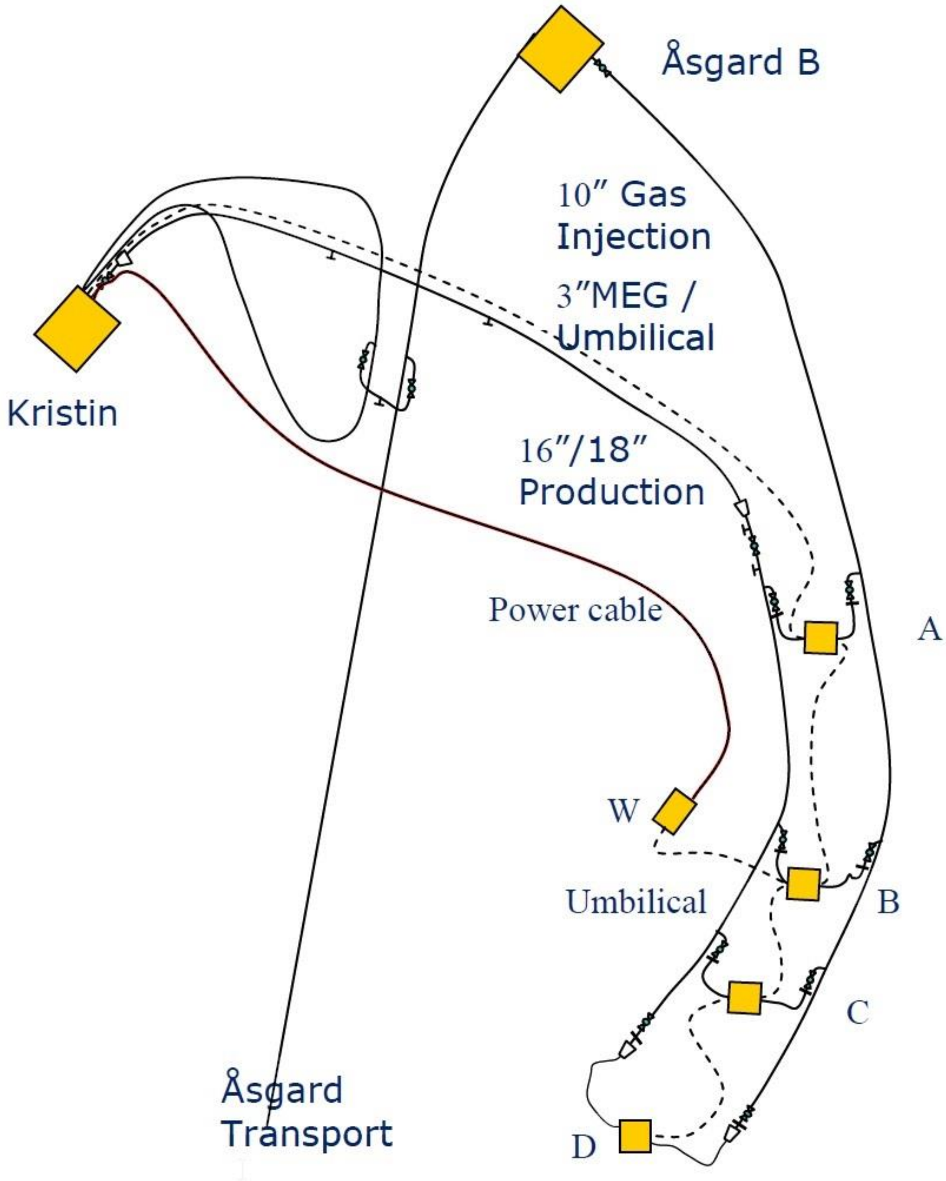


Figure 3.8-2: *Tyrihans field layout* [38]

A set of considerations must be faced during the tie-in of the Maria gas lift line. Statoil will utmost avoid depressurizing the gas lift line since there is a high risk of influencing production on the entire Tyrihans field. Tyrihans template D is fitted with a full bore, DPE-valve as the primary barrier between the gas line toward Åsgaard and the future connection point of Maria gas lift line. This valve is referred to as Valve-51.

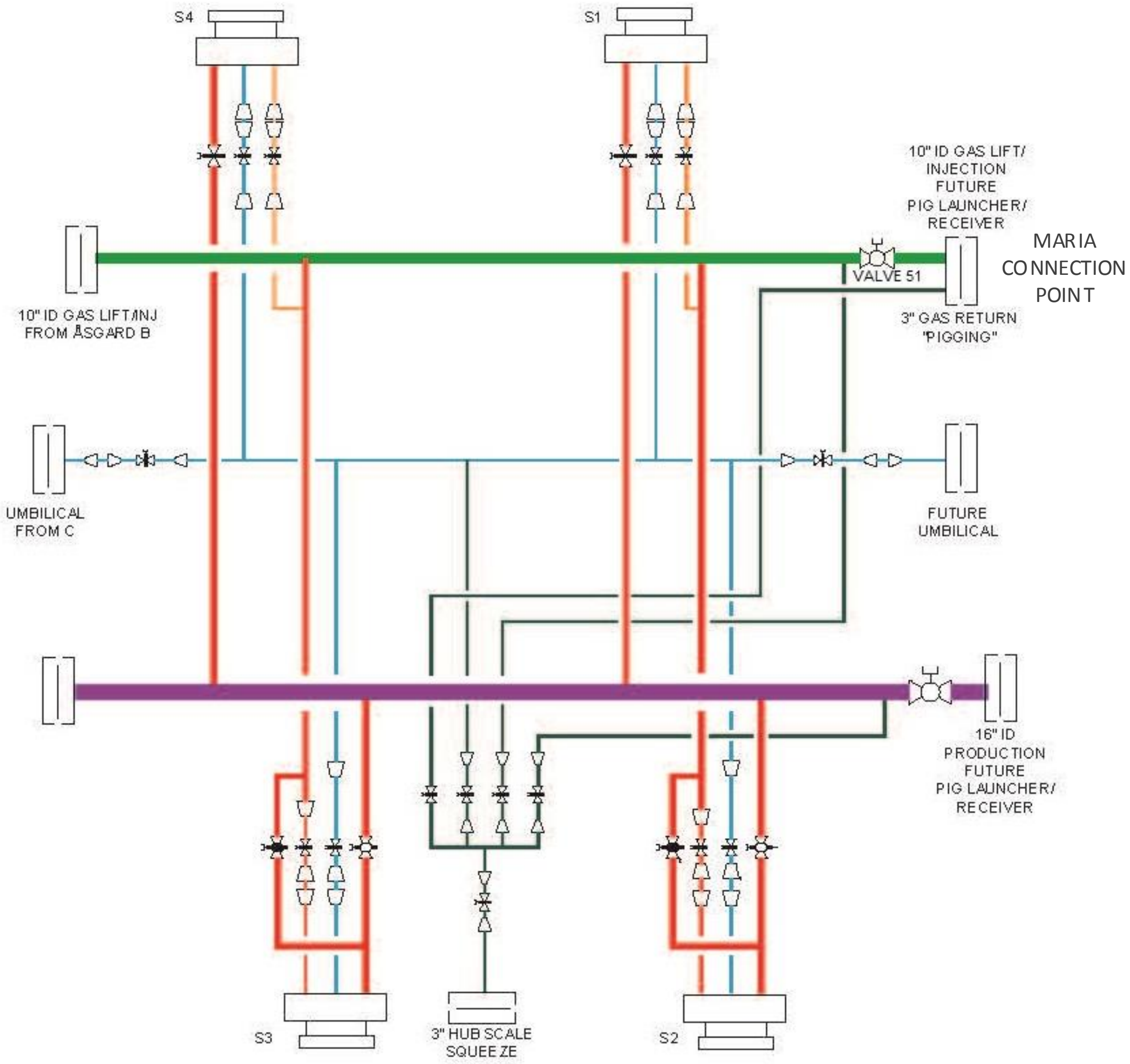


Figure 3.8-3: *Simplified manifold schematic, Tyrihans template D* [39]

The manifold end in Figure 3.8-3 after valve-51 is fitted with a high-pressure cap with test and flushing possibility. This means that in additional to the barrier function flushing/testing is possible through a small bleeder valve. The bleeder valve at the cap can be opened by ROV to release pressure contained between valve-51 and pressure cap. If valve-51 seals completely, the bleeding valve will stop gas release when the gas pressure reaches the hydrostatic pressure in the position of the outlet. The flushing valve (normally used to inject preserving fluid) is also recommended to open to be sure the reduction of gas release in bleeding valve not is caused by plugging.

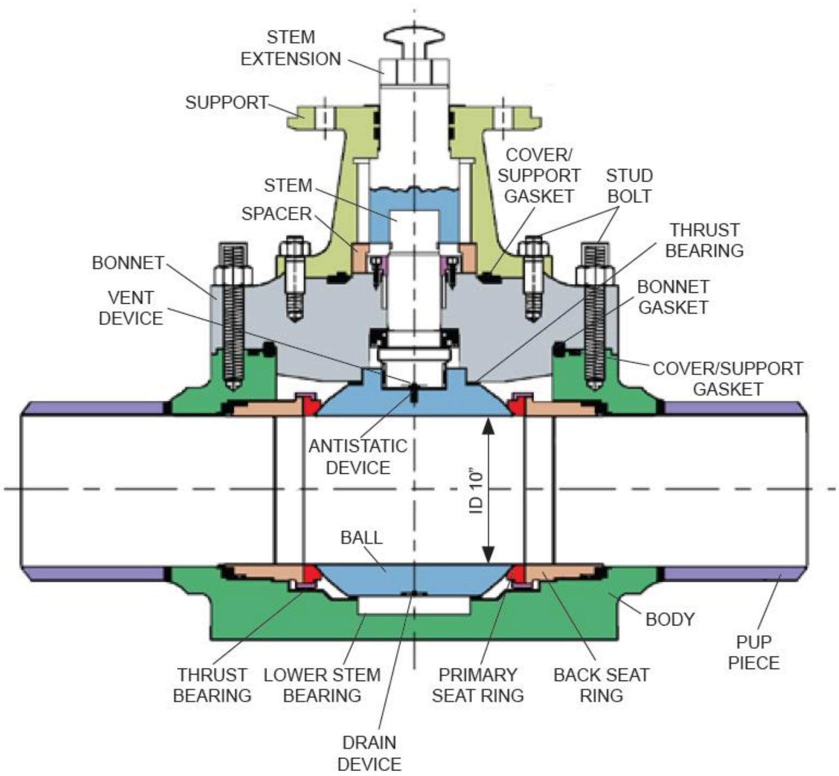


Figure 3.8-4: *DPE Valve* [39]

Valve-51 at Tyrihans template D is a critical process part to the gas lift commissioning procedure. Valve-51 is an ROV operated ball valve with dual piston effect. This means it contains two barriers and should be able to isolate high pressure in both directions. The drain device indicated in the bottom of Figure 3.8-5 is not possible to open by ROV, but rather a device to be used in the workshop.

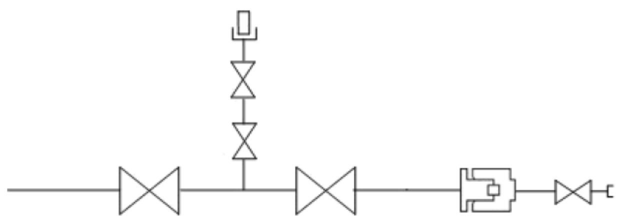


Figure 3.8-5: *Double block and bleed* [40]

Wintershall holds a subsea isolation philosophy [40]. This clearly instructs on a procedure of two barriers between environment and hydrocarbons under pressure. Wintershall isolation philosophy shows how a double block and bleed is to be performed towards hydrocarbon under pressure. Valve-51 is considered as two barriers, but bleeding between these two barriers is not possible. The Wintershall isolation philosophy is not 100% obtained in any case of tie-in if the high-pressure cap is removed while the Tyrihans gas lift line is pressurized.

Statoil holds an isolation philosophy with an exception for the use of only one barrier on short-term interventions such as a spool tie-in or PLR connection. The remaining barrier must be proven to seal. The Tyrihans gas lift pipeline consist of ~1900m³ of 310bar pressurized natural gas consisting of ~80% Methane [32]. This corresponds to 589 000Sm³ of natural gas. If this barrier is breached not only safety to personnel on vessels in the area may be at risk but a major discharge to the environment may also be a consequence.

Figure 3.8-6: *ROVCON* [41]

The tie-in technique selected is a FMC developed remote operated vehicle connection tool (ROVCON), the operation is first to winch the spool to the position where a hydraulic connection tool may be positioned to perform cleaning and final connection. The winch is connected to the template, so forces induced will have little to no effect on valve-51.

Figure 3.8-7: *ROVCON collet connection tool* [42]

The final hydraulic connection tool is a collet connection tool. This tool is very powerful and presses the two flanges towards each other and seal by hydraulic pushing the collect lock mechanism in place. This operation is performed less than one meter downstream of the critical valve-51. It should be considered a possibility that this connection may cause the valve to leak. A risk assessment should be performed regarding this operation. The responsibilities should be decided up front in hence of an unwanted accident resulting in a discharge of hydrocarbons.

3.9 De-watering of the tie-in spool and Tyrihans GL PLEM

The assumption is made that connection is made with a proven sealing valve-51.

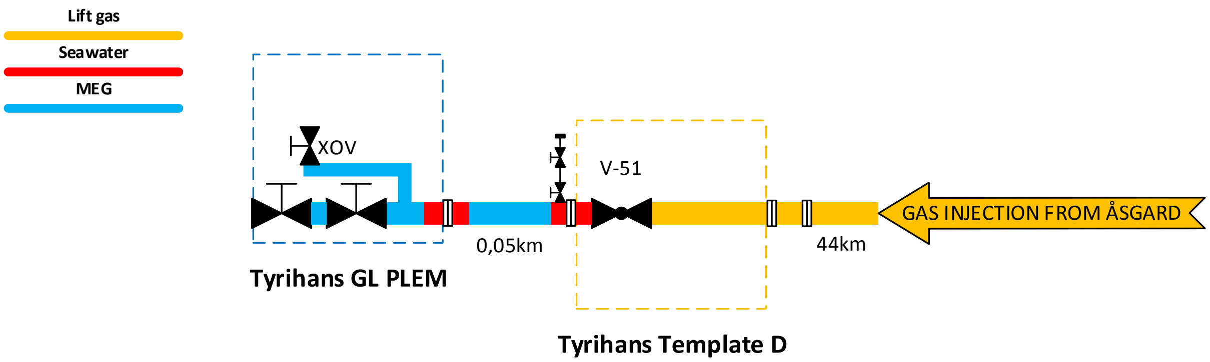


Figure 3.9-1: *Spool connection*

The spool connecting Tyrihans GL PLEM and Tyrihans template D is fitted with end caps, and MEG filled, before installation to minimize seawater ingress. Some seawater ingress must be expected at each connection point.

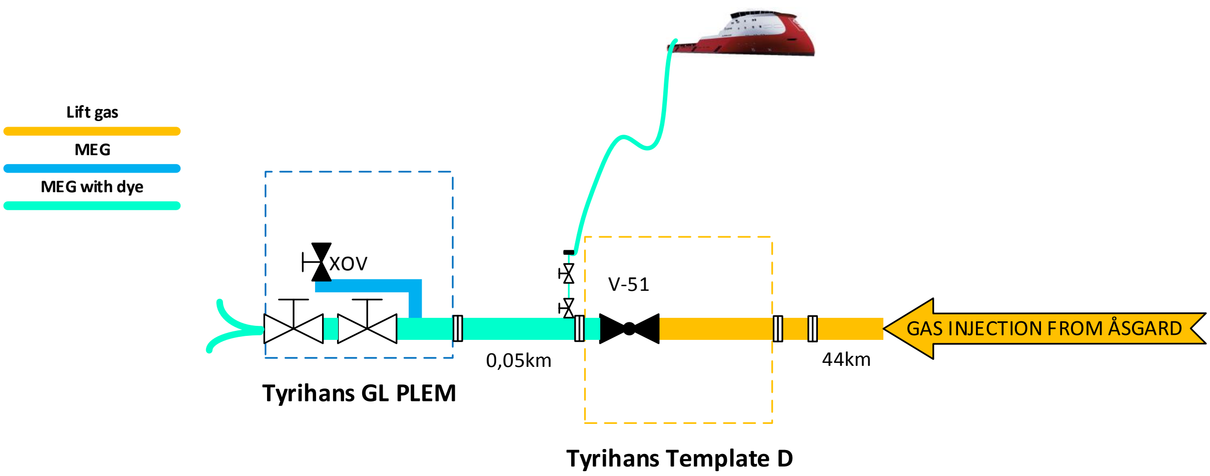


Figure 3.9-2: *Spool flushing*

After the connection has been performed a stab connection at the 10''spool close to Tyrihans template D is used to flush out seawater and displace the fluid by MEG with dye to perform pressure testing.

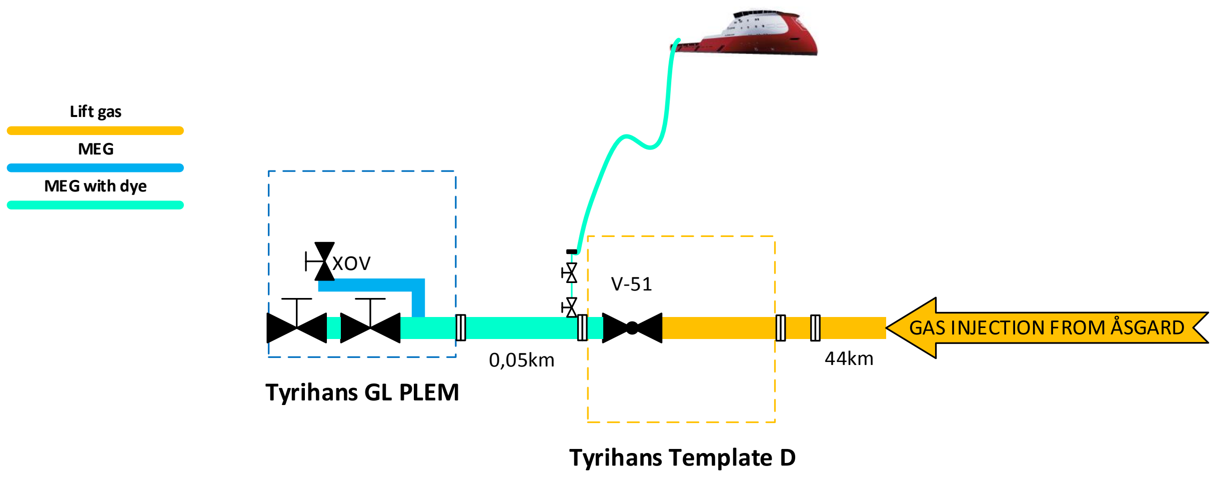


Figure 3.9-3: *Pressure and leak testing*

After flushing, valves at the end of the GL PLEM are closed, and the section is pressurized to perform a pressure and leak testing.

3.9.1 Drying Option A – System loop purge

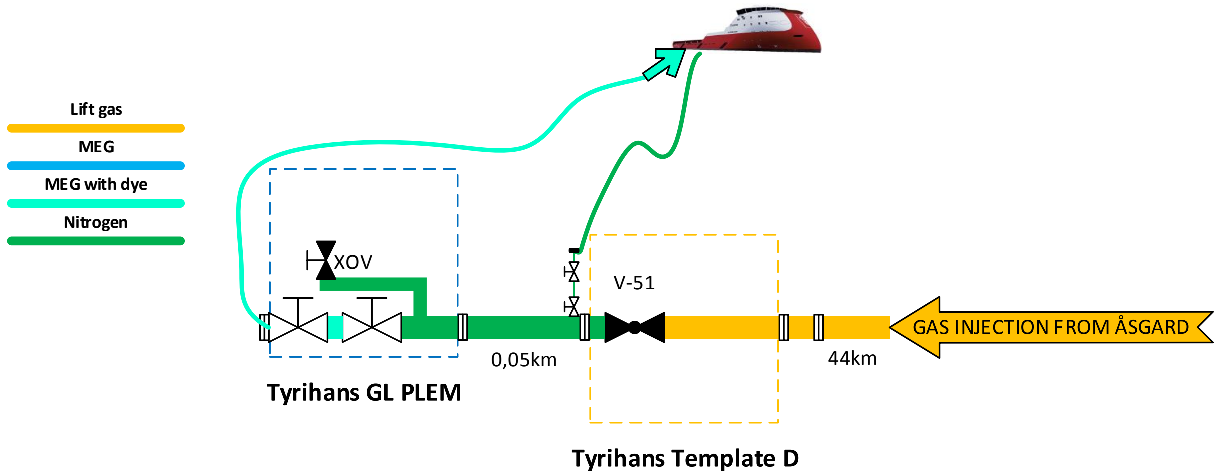


Figure 3.9-4: *Displacement and purging*

Nitrogen is purged until dryness is achieved, the leg to the XOV should be self-draining. The purging direction is selected to flush out residues at the lowest point. By connecting both inlet and outlet, measuring of dryness of the system is made possible.

3.9.2 Drying Option B – Purge to sea

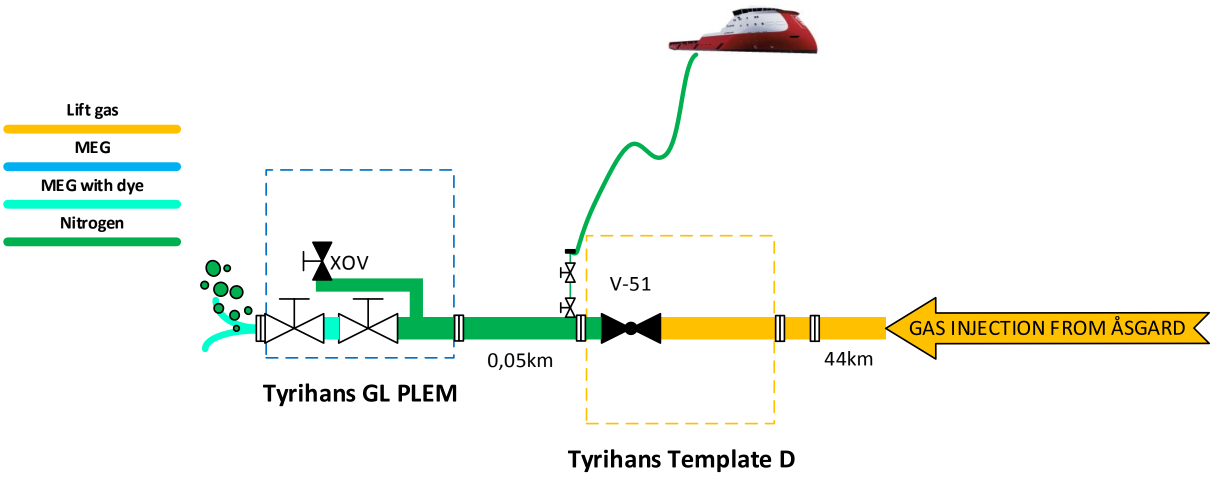


Figure 3.9-5: *Displacement and purging to sea*

By the use of one, connection point operation time is reduced. The MEG residues are displaced to sea, and the system is continued purged for some time to ensure dryness. The dryness of this section will not be measured by the use of this option, and with this uncertainty follows a risk of hydrate formation. As a safety measure purging should be performed much longer than anticipated to achieve, the dryness recommended.

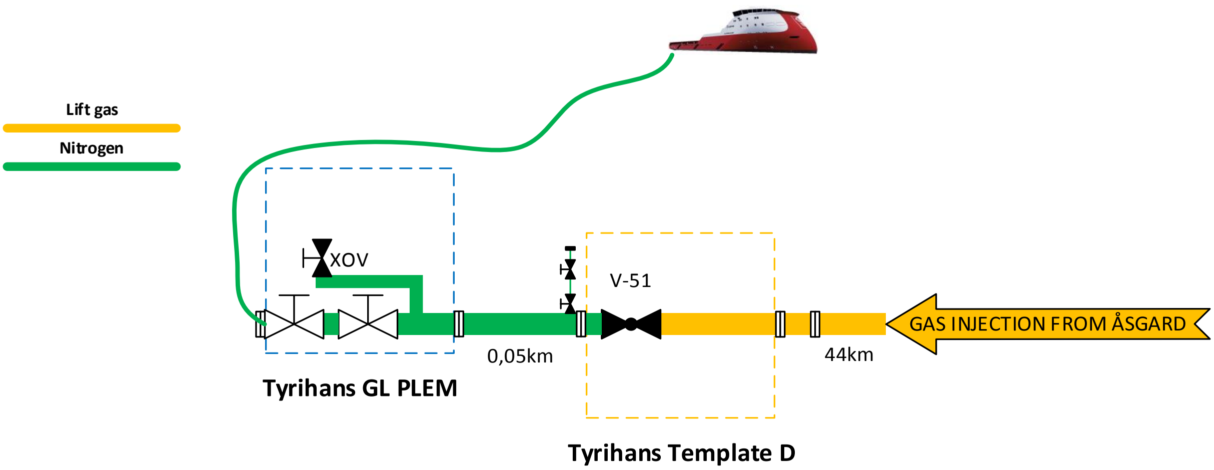


Figure 3.9-6: *Pressurization*

The system is pressurized to 40bar to equal out pressure difference over XOV prior to opening.

3.10 Pressurization

This part is highly dependent on the leak testing performed on valve-51. If valve-51 does not prove to seal adequately option B is the only solution viable.

3.10.1 Option A – Nitrogen pressurization

This procedure requires a large volume of Nitrogen. 123 tons of liquefied nitrogen is needed to pressurize the gas pipeline to 309 bar assuming the gas temperature is higher than 0˚C [Appendix C].

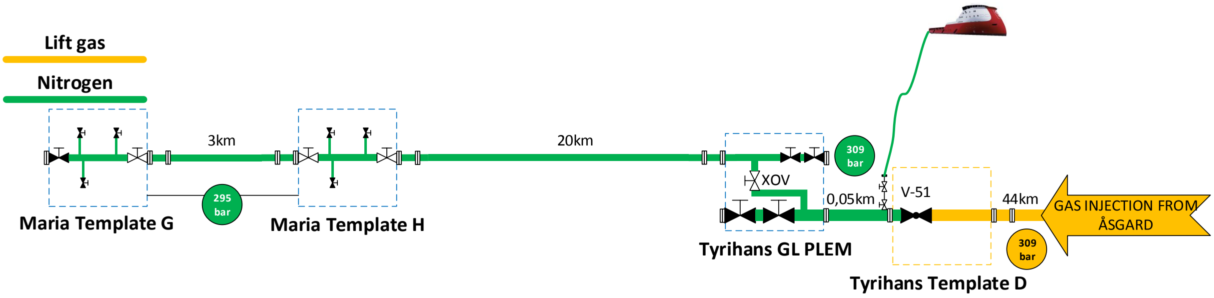


Figure 3.10-1: *Pressurization*

The Tyrihans gas injection system is first depressurized as low as possible during production. This is done to reduce the amount of Nitrogen necessary at Maria. After final drying of the Tyrihans 10-inch spool pressure is increased to match the pressure in the 6-inch system. When the pressure is approximately equalized, XOV is opened. Nitrogen is continuously injected until the pressure at Maria template G is measured to be approximately equal to the Tyrihans gas lift pressure.

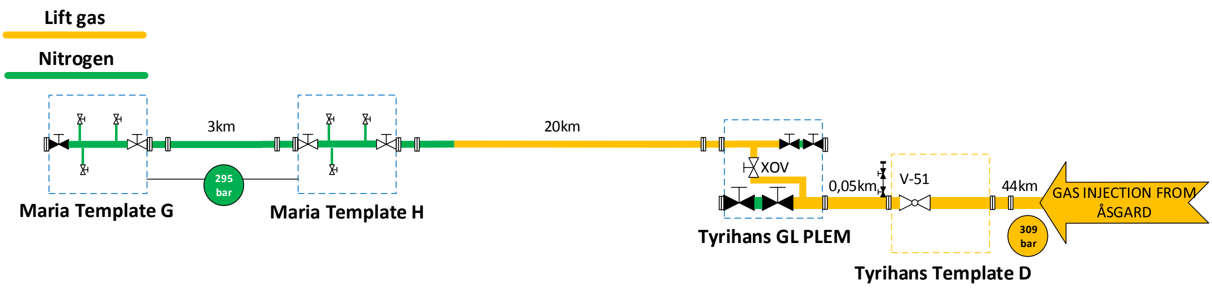


Figure 3.10-2: *Displacement to wells*

When the pressure is equalized to Tyrihans gas lift pressure valve-51 is opened. The Nitrogen is then injected in the annulus of the producing wells. Flow assurance at Wintershall [43] has calculated the pressure loss in the Maria gas line to be 14bar under production.

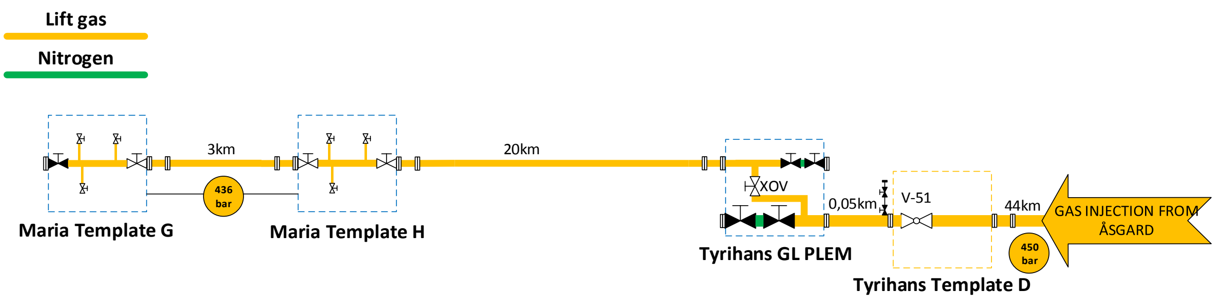


Figure 3.10-3: *Pressurize to operation pressure*

As soon as Maria gas lift injection has started up operational pressure is re-established in the complete system from Åsgaard.

3.10.2 Option B – Depressurization of the Tyrihans gas lift line

For this case, the complete Tyrihans gas lift system must be depressurized. One concern is that Tyrihans field will need to be partially shut down, and gas lift injection need to be stopped for a period. Depressurizing must be performed at Åsgaard B by flaring off the gas in Åsgaard B - Tyrihans gas line. Statoil has on NCS a no-torch policy. So this is a topside issue and concern at Åsgaard B.

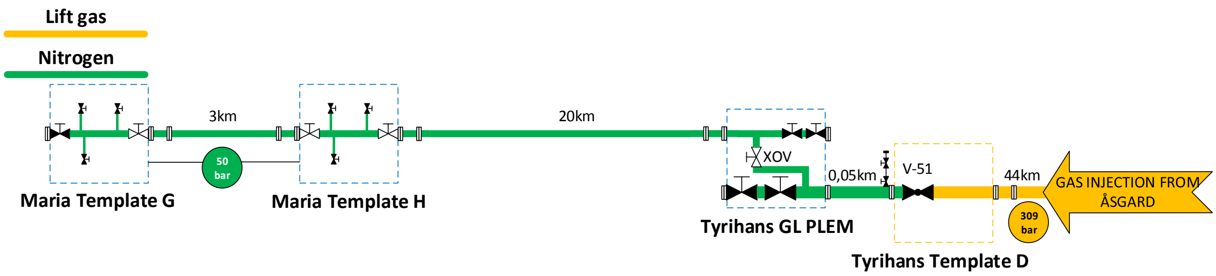


Figure 3.10-4: *Open XOV*

The XOV is opened, and vessel disconnected, the Maria gas lift line is ready for pressurization. The pressure at the Åsgaard B - Tyrihans gas lift line needs to be decreased to equal out the pressure over valve-51.

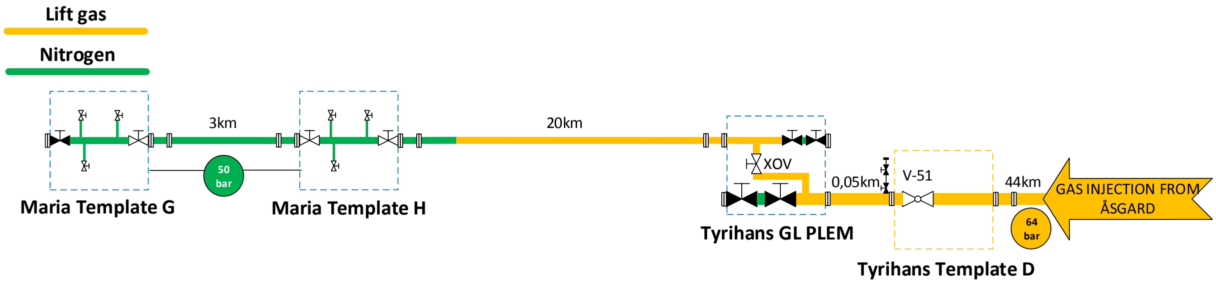


Figure 3.10-5: *Decrease pressure on the Tyrihans gas lift*

When Tyrihans gas lift line reaches the pressure of the Maria gas lift system, valve-51 is opened.

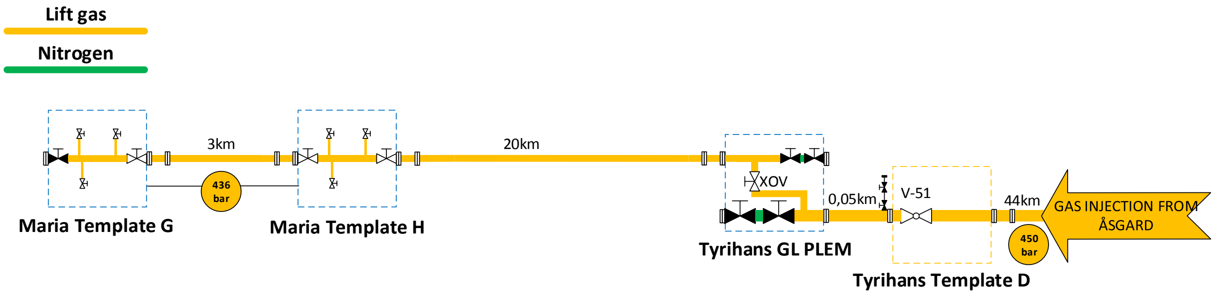


Figure 3.10-6: *Increase pressure*

The complete system is now pressurized all the way from Åsgaard B unit to the Maria wells, and the nitrogen will be displaced through the Maria well stream system towards the Kristin production unit.

3.10.3 Option C – Bypass pressurization

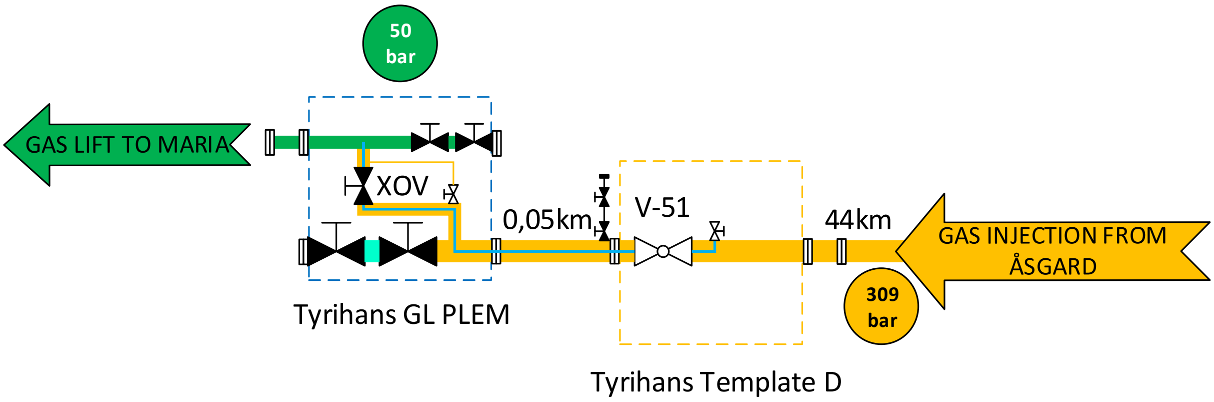


Figure 3.10-7: *Pressure testing*

The concept of bypass pressurization is to install a smaller branch in parallel with the XOV. This valve must be able to open with a large differential pressure and must contain flow control capability.

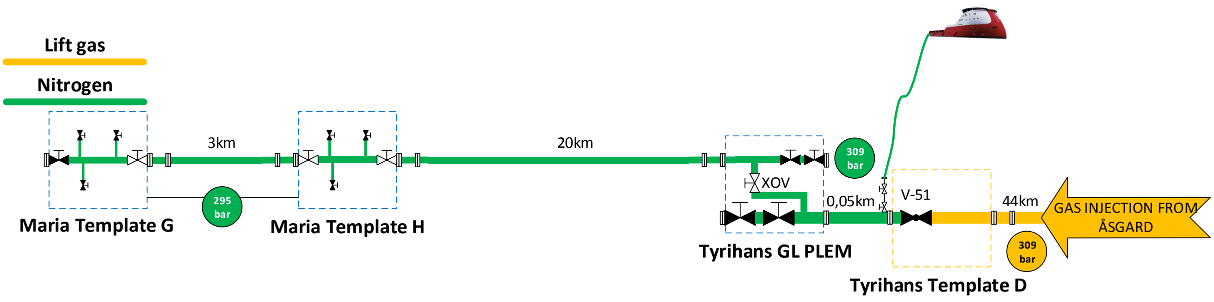


Figure 3.10-8: *Valve opening*

After drying the Tyrihans GL PLEM it will be pressurized with nitrogen to equalize Tyrihans gas lift pressure. When pressure has equalized, valve-51 is opened.

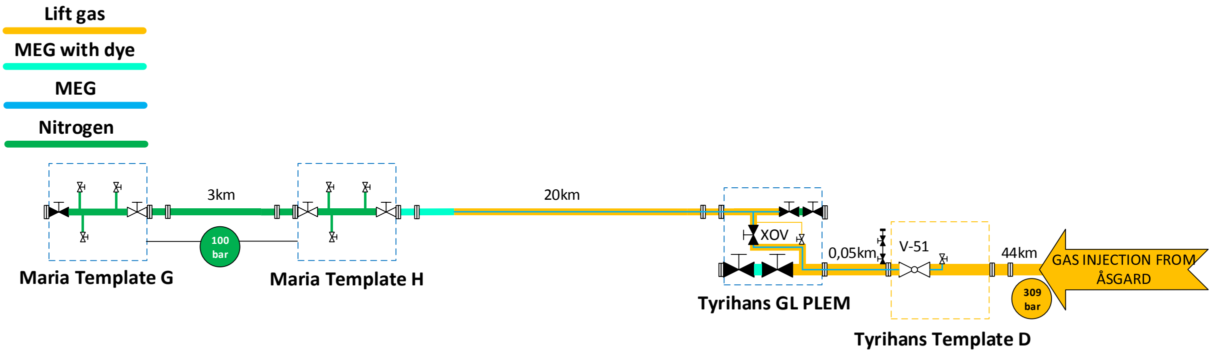


Figure 3.10-9: *Open bypass valve*

The bypass valve to the XOV is opened very slowly to start pressurization and introduction of hydrocarbons. The high differential pressure over this valve will cause a cooling effect (Joule-Thompson effect). The gas properties of the gas from Åsgaard should hold at least a dryness with dewpoint -18˚C at 79barg [32]. This means that may temperature decrease below 18˚C at a pressure of 79 bar water will be extracted. And at this temperature hydrates may form inside the pipeline with a risk of plugging. There is also a danger of ice to form on the outside this valve considering it is surrounded by seawater. The danger of outside ice is a non-operational valve. The valve will be locked in the set position as long as ice covers it.

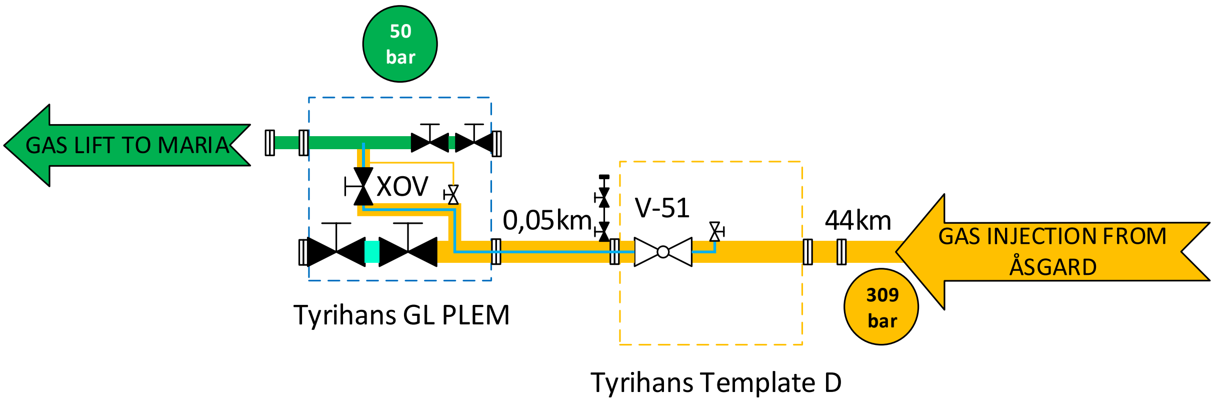


Figure 3.10-10: *MEG inhibition*

The accumulation of hydrates forming inside the bypass leg is possible to prevent by injecting MEG into the GL PLEM from the Tyrihans template D. The MEG will act as a heating fluid and antifreeze agent. This MEG has to be injected at the Tyrihans template D from the service line continuously. These residues will build up at low points in the gas line towards Maria.

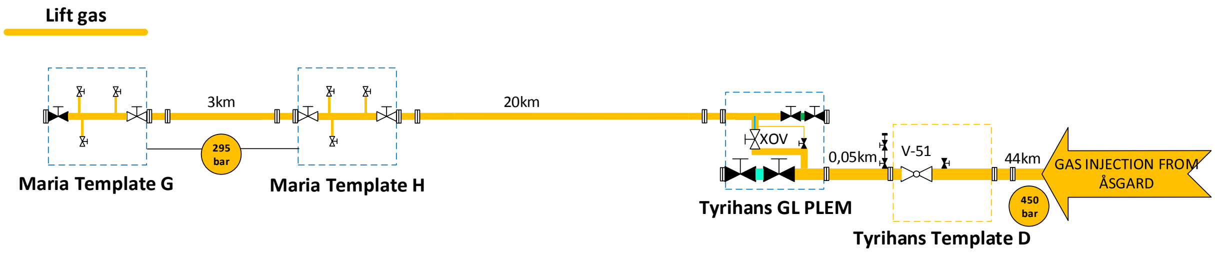


Figure 3.10-11: *Pressurizing*

After pressure equalizing, the XOV is opened, and the bypass valve closed. Nitrogen and MEG fractions are displaced to the annulus of the wells and then into the well during production. It is assumed that most of the MEG residues will remain in the Maria gas injection pipeline.

Points of considerations to evaluate if this are a viable option:

- Internal hydrate formation
- External icing
- Is open/close valve adequately or should a choke valve be introduced.
- MEG injection point is approximately 100m from the point of concern.
- MEG consumption and residue buildup
- Pigging at operating pressure to remove MEG residues

The main drivers of this option are not to affect the production on Tyrihans.

3.11 Pressurization evaluation of the gas lift system

Area of importance	Multiplication factor	Option A : Nitrogen pressurization	Value A	Option B: De-pressurize Tyrihans gas lift	Value B	Option C: Bypass pressurization	Value C
Safety to personnel in operation	x5	Liquid nitrogen handling	-1	Flaring at Åsgaard	-2	No significant issues	0
Environmental consideration	x4	No large issues	0	Flaring at Åsgaard	-2	No significant issues	0
Integrity of procedure	x3	Integrity of the system is good	2	Best procedure from Maria prespective	2	Cooling effect and MEG consumption	-2
Interface issues to host	x2	Nitrogen handling in first production	-1	Large impact	-2	Good solution	2
Cost	x1	Large nitrogen consumption	1	Large in hence of impact on Tyrihans	-2	Re design of SPS and MEG consumption	-1
Total evaluation sum:			**1**		**-7.4**		**-1.2**

Table 3.11-1: *Evaluation sheet of pressurization*

3.11.1 Summary of evaluation of gas lift system pressurization

Option A: Nitrogen pressurization

This procedure requires safety measures to be in place when handling liquid nitrogen, especially in lifting procedures on loading thanks on the commissioning vessel. The amount of nitrogen used for pressurization must be flared at Kristin as it is produced with the first oil.

Option B: Depressurize Tyrihans gas lift

Integrity wise from Maria perspective this is the best procedure. Depressurizing the gas lift line of Tyrihans will affect production and possibly stop the complete production from Tyrihans. Another issue is how to depressurize this system. Evidentially all the gas must be flared at Åsgard to depressurize the pipeline.

Option C: Bypass pressurization

The idea of a bypass valve is a lucrative option at first sight. But further evaluation found the cooling issue due to the Joule-Thompson effect to be a show stopper. The cooling effect will cause temperatures below dewpoint of the pipeline and water residues may cause hydrates to form. Pipeline material spec is also being challenged by the low temperatures. MEG injection in front of the bypass valve from the Tyrihans template D is suggested. MEG consumption for this purpose is quite considerate and additional liquid introduced into the dry pipeline is not desired.

3.12 Identified points of optimization and conclusion

Option A: Nitrogen pressurization offers the largest flexibility, as long as valve 51 proves to seal this should be the preferred option. To optimize this procedure, Statoil may decrease pressure on the gas lift line from Åsgaard to a still operational pressure. If this is performed, nitrogen consumption on pressurization can be reduced. The main objective is not to affect the production on Tyrihans. Although the volume needed for pressurization is quite large, it is manageable. Ten tanks of $20m^3$ which in total contains $165m^3$ liquid nitrogen are necessary to reach 309 bar in the pipeline. A heater must also be used to increase the temperature of the liquefied nitrogen, so it evaporates to gas form.

4 WATER INJECTION SYSTEM

The water injection system is somewhat different compared to the other systems since it has an inner pipeline lining. The inner layer of the water injection pipeline is of a PE compound to protect the metal pipe against corrosion. To further protect pipelines on the production side the water used for injection purpose contains only small amounts of oxygen. The SRP on Heidrun TLP removes sulphate-ions, oxygen and salt from seawater [24]. The inner PE-liner is also helping prevent scaling in the pipeline since the surface roughness is very low, high water flow alone may be enough to keep the pipeline clean. A possible issue for PE-lined systems with high pressure is the danger of gas to diffuse through the liner and get trapped between the PE-liner and the first metal layer. At depressurization gas will expand and may in some cases rip the liner from the metal and cause partially or complete blocking of the pipeline. This is why gas is unwanted as part of the injection water.

4.1 Pre-commissioning of the water injection pipeline

Since this pipeline has a PE-liner, millscale and welding residues inside is not a concern. The purpose of the pigs is only to act as a displacement pig to best evacuate air from the system. Foam pigs are the only pigs compatible with the soft PE-liner, so these are proposed to use for displacement. The depth of the pipeline varies between 275-345m. Lowest point of the pipeline is at Heidrun riser base [44]. Flooding of a pipeline without the use of pigs is best fitted where the pipeline is stable increasing from low to a high point. This extracts the gas with the flooding direction. Heidrun TLP is the highest point but the seabed bathymetry survey has discovered many high and low point between Heidrun riser base and the Maria field. A high-velocity flushing is an option to extract air from these pockets, but then again a vast pumping unit must be in place to displace a 3833m3 volume of the pipeline. For the purpose of a better result with only small volumes of air remaining and to shorten down the flooding time, foam pigs should be used. Flooding velocity will be lower by the use of pigs, but the intention is to avoid long flushing time after final flooding.

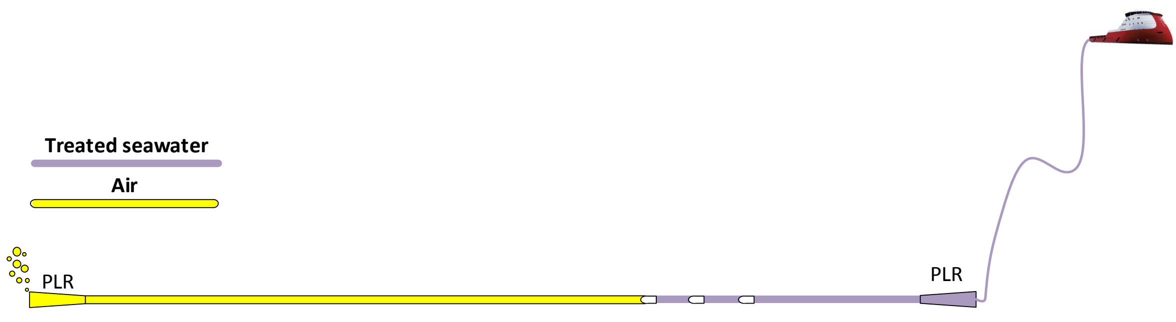


Figure 4.1-1: *Flooding and cleaning*

Displacement and cleaning are performed with the foam pigs, but gauging will not be performed because of the soft PE liner.

Figure 4.1-2: *Air evacuation and pressure testing*

After displacement and all pigs are visually received at the partially open receiver, flushing continues for a period to extract any air residues to have slipped the three pigs. The pipeline is then sealed, and pressure tested.

4.2 Water injection system battery limits

Sufate reduced water for injection purposes is supplied from Heidrun TLP. This is the longest of the pipelines introduced in the Maria development and also contains a flexible riser up to the Heidrun facility. The pipeline is intended to be PE-lined to reduce corrosion possibilities. At the same time, this relatively soft inner liner reduces the use of standard pigs and how to displace treated seawater must be considered. The pipeline including riser is provided by Wintershall. The battery limit towards Statoil is from the topside riser termination unit at Heidrun. Operationally the water injection line may use topside injection pumps and a large amount of treated water for the commissioning. This commissioning should not influence the production at Heidrun.

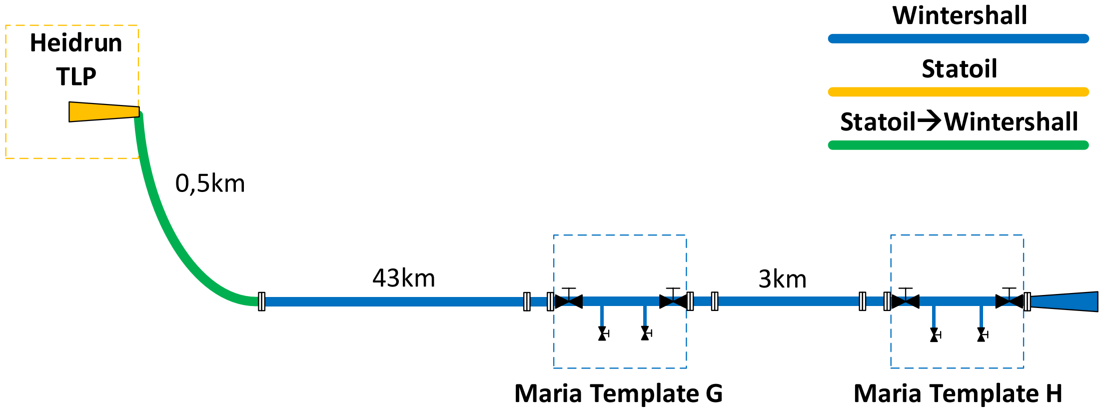


Figure 4.2-1: *Water injection system overview*

The water injection system is tied back to the Statoil Heidrun platform. This is because Heidrun has the capability to supply the Maria field with produced water for injection purposes. Heidrun is Statoil operated, and the riser is also provided by Statoil.

4.3 Considerations to commissioning strategy

The WI-pipeline is the longest installed pipeline to the Maria project and arrives after 43km at the north side of Maria template G. The pipeline has a nominal bore of 12-inch. The pipeline is PE-lined since this is of a lower grade carbon steel compared with spools and manifolds that are not PE-lined. Air in the water injection system is the highest concern since the air may permeate through the liner at high pressure and get trapped behind the liner. When depressurizing the pipeline, the air will expand and unbound the liner off the inner metal pipeline. This is why it is important to evacuate air from the complete system.

4.4 Commissioning start-up

The commissioning for the start-up has been evaluated by two different options.

- Option A – Displacement by foam pigs
- Option B – Displacement by flushing

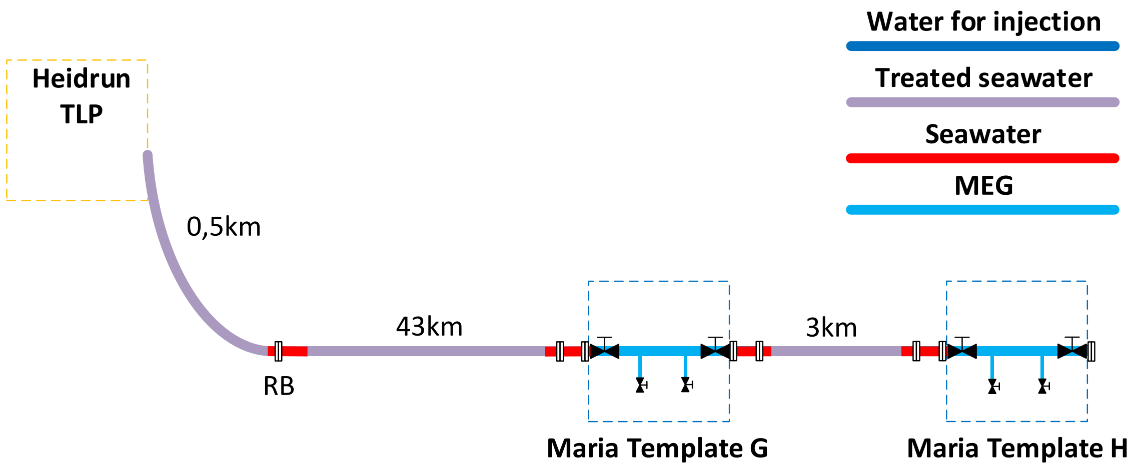


Figure 4.4-1: *Water injection system after tie-in procedure*

During tie-in of spools to connect manifolds and riser base, some seawater ingress is expected. The riser is filled with treated water after connection and flushed to evacuate air in the sag bend toward riser base. Both manifolds are pre-filled with MEG and sealed off by closing all valves.

4.4.1 Option A – Displacement by foam pigs

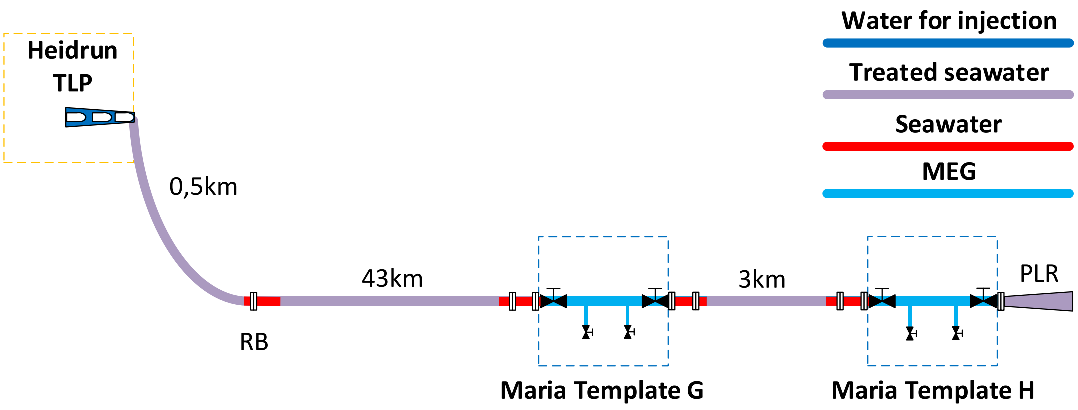


Figure 4.4-2: *PLR connection*

The option of displacing with foam pigs requires a PLR at Heidrun TLP and one at Maria template H. These are installed as last part of the tie-in procedure. During PLR installation, all valves remain closed.

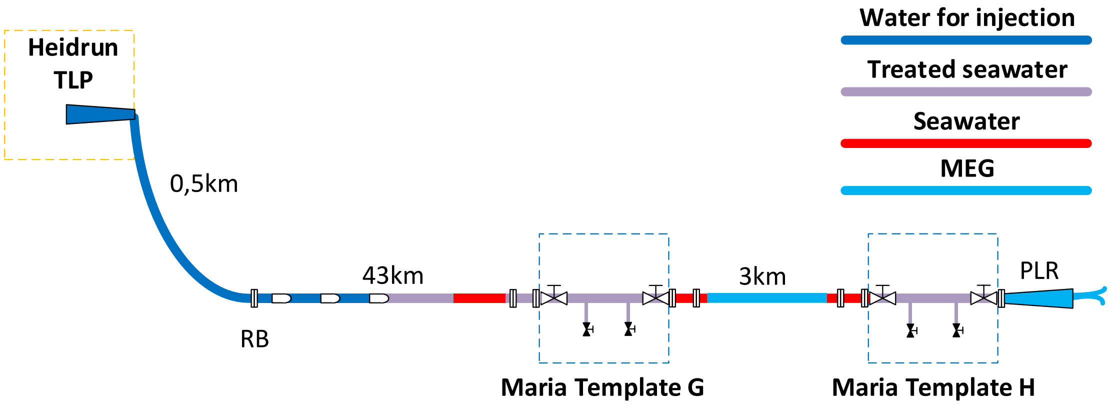


Figure 4.4-3: *Foam pigging*

The foam pigs are inserted at the Heidrun TLP. The three pigs are displaced by 10m³ water for injection; this corresponds to two slugs of ~150m. The flow of water for injection from Heidrun is regulated for keeping a stable flow of ~150m³/h to achieve a pigging speed of approximate 0.5m/s. Pressure should be measured to track pigging movement. A stable pressure indicates a stable velocity of the pig train. Note that some variations must be expected in pressure because of the seabed bathymetry high and lows. The pigging alone will take approximately 25 hours.

$$Pigging\ duration = \frac{l}{v} = \frac{45\ 000m}{0.5m/s} \approx 25hours$$

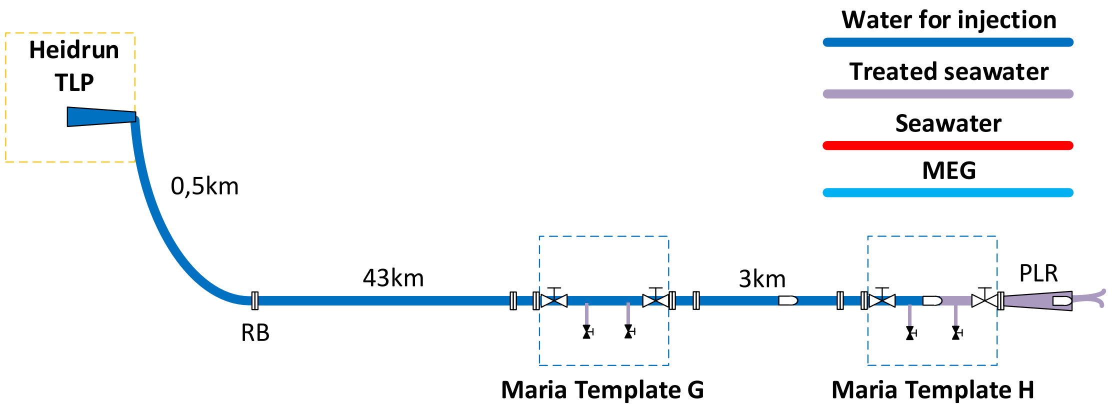


Figure 4.4-4: *Displacement by foam pigs*

Topside flow measurement and pressure gauge indicate the location of the pig train. A noticeable pressure reduction indicates the arrival of the first pig, and similar to the next two pig arrivals.

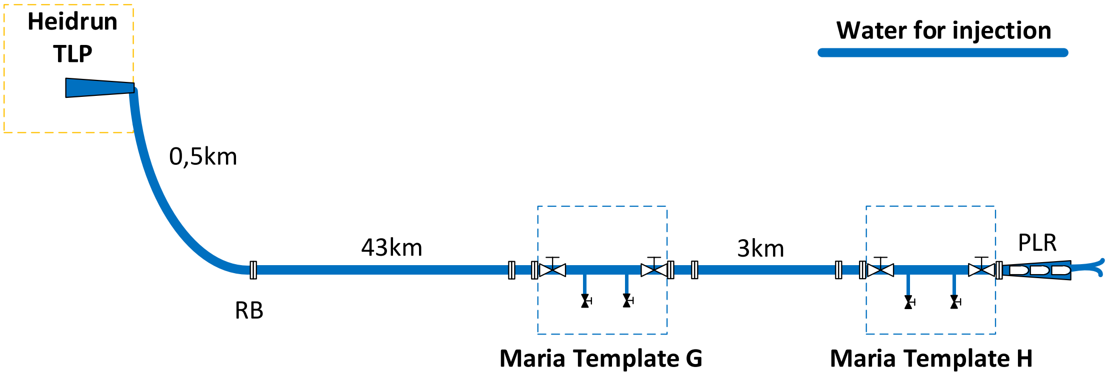


Figure 4.4-5: *Pig arrival*

The valve at the end of the manifold at Maria template H is closed while flushing to exclude the possibility of seawater ingress. The system is pressure tested to a level higher than anticipated operational pressure and is ready for operation.

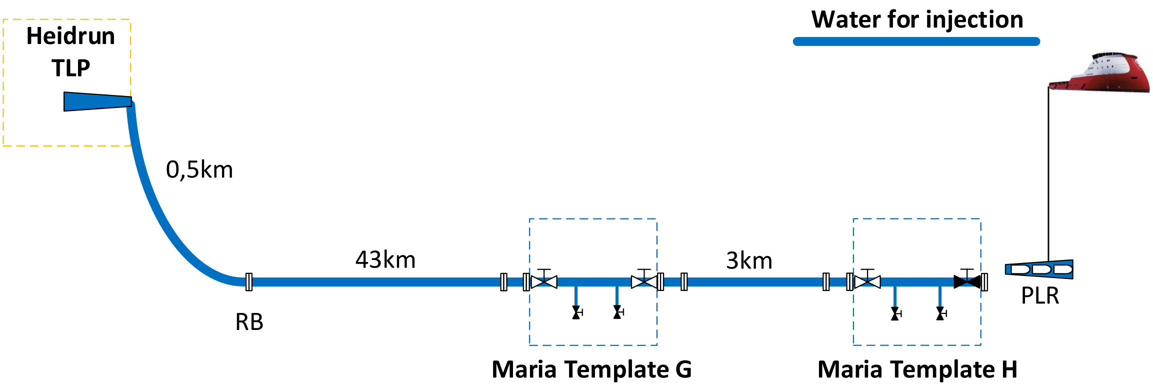


Figure 4.4-6: *PLR removal*

After commissioning Topside PLR is disconnected, and the subsea PLR is removed by a vessel.

4.4.2 Option B – Displacement by flushing

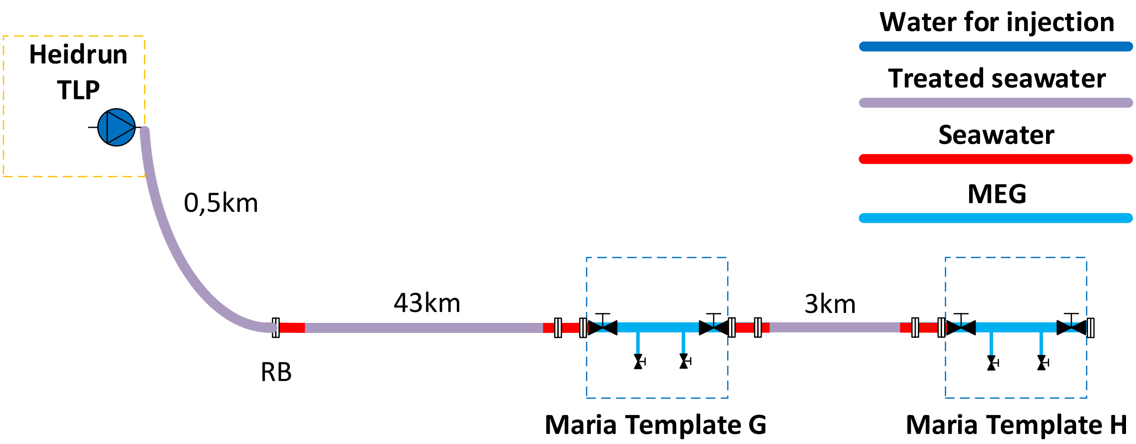


Figure 4.4-7: *SRP start-up*

After tie-in is completed, the in-line valves at Maria template G are opened. The SRP pumps are started, and air in the riser is vented topside. A flow test of the SRP should be performed before connecting to the topside riser. When the SRP is ready to inject, the valves at Maria template H is opened.

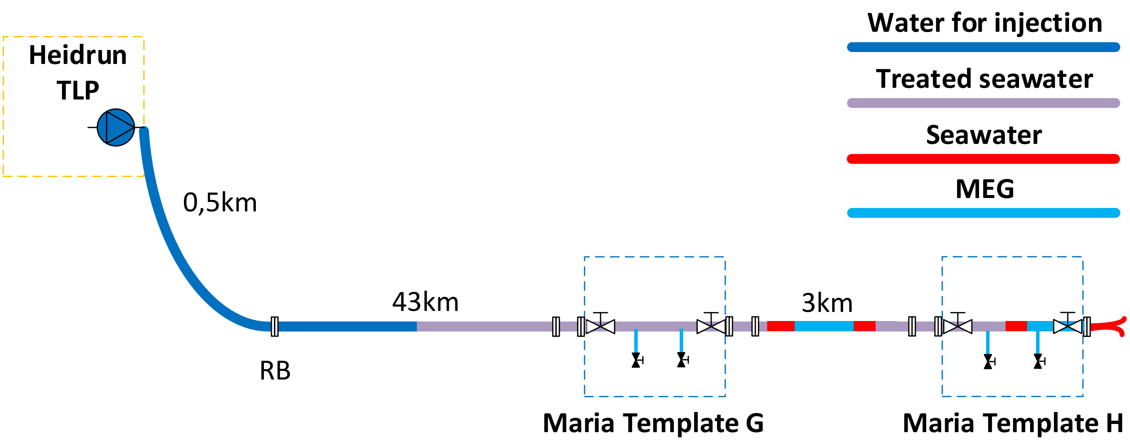


Figure 4.4-8: *High-velocity flow*

The treated water inside the pipeline is displaced directly with water for injection at a velocity as high as possible. This velocity must be sufficient related to the friction factor of the inner layer of the pipeline to create plug flow. With plug-flow, mixing of the treated freshwater and injection water is limited. Air is also better vented out with plug flow.

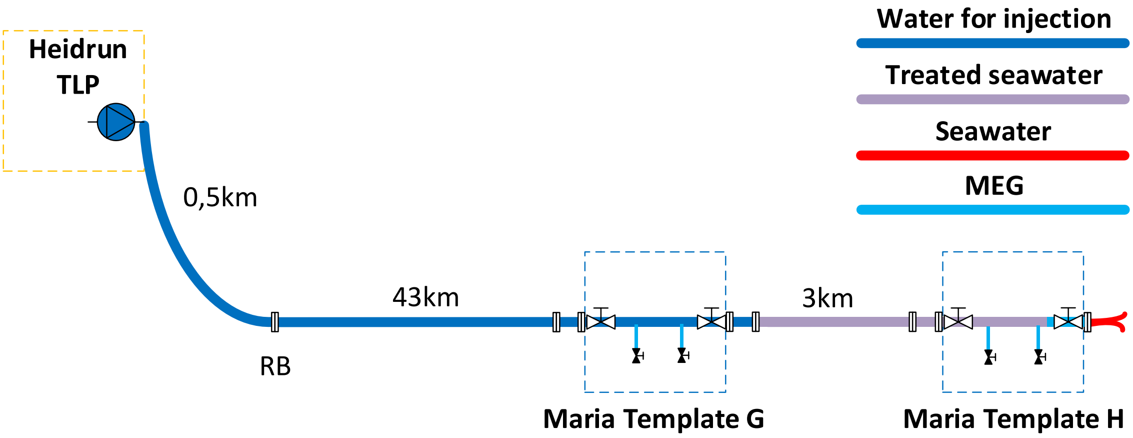


Figure 4.4-9: *Displacement and residues*

Residues will remain in the branches toward the water injection XT at both templates. Therefore, manifolds are filled with MEG and sealed before installation.

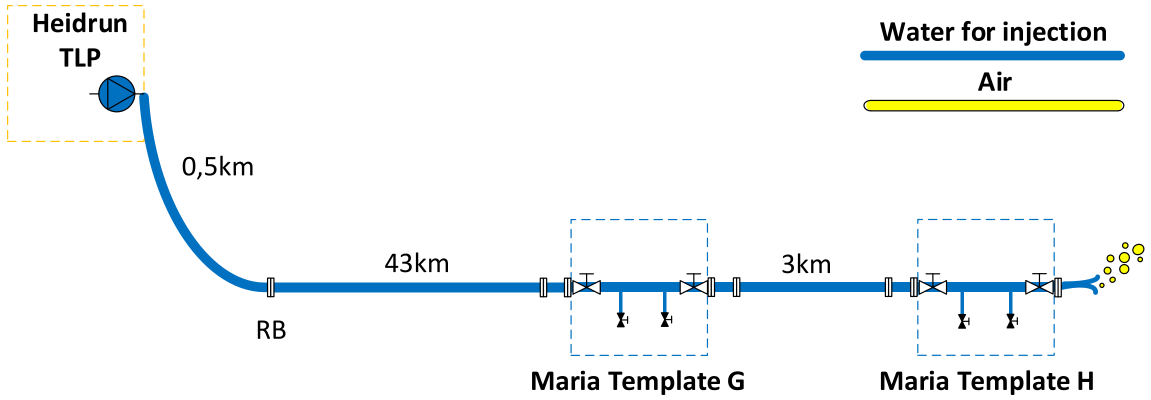


Figure 4.4-10: *Displacement and residues*

Flushing is continued until there is no trace of the dye in the treated water and no more air vents through the outlet. The flushing will be ROV monitored.

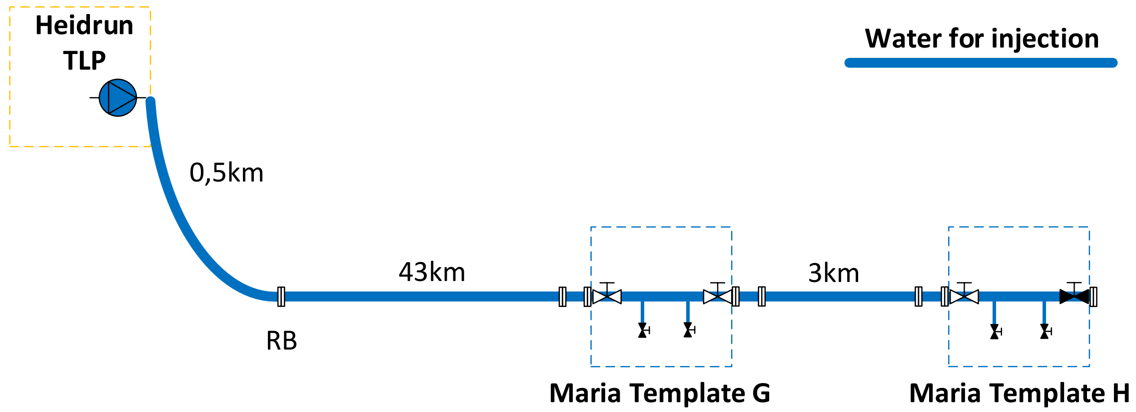


Figure 4.4-11: *Displacement and residues*

At the point where flushing seems to be sufficient the end valve at Maria temple H is closed while the SRP at Heidrun continues to increase pressure. The end-cap is fitted, and the area between valve and cap flushed and filled with MEG for prevention purpose. The system is pressure tested by increasing pressure to above operational pressure and the system is ready for operation.

4.5 Displacement evaluation of the water injection system

Area of importance	Multiplication factor	Option A : Displacement by foam pigs	Value A	Option B: Displacement by flushing	Value B
Safety to personnel in operation	**1.4**	Require more lifting	0	Quite safe procedure	1
Environmental consideration	1.3	Environmental friendly fluid	0	Environmental friendly fluid but double amount in use	-1
Integrity of procedure	1.2	Foam pig have the risk of dissolving over long distances	-1	High velocity flushing is less effective regarding air evacuation	-2
Interface issues to host	1.1	Foam pigging is time consuming and the pig receiver must be removed after operation	-1	Little equipment necessary for operation.	0
Cost	1.0	Expensive in vessel usage and time consumption	-1	Cost effective operation	1
Total evaluation sum:			**-6**		**-4**

Table 4.5-1: *Evaluation sheet of water injection displacement*

4.5.1 Summary of evaluation

Option A: Displacement by foam pigs

Regarding air evacuation, the use of foam pigs is the best option. But the risk of foam pigs to dissolve by long distance pigging is present. Foam pig producers [15] are stating that pigging at distances lower than 100km is not critical for a foam pig to dissolve, the risk is still present because of manifold branches the pig has to pass. Duration of the pigging procedure alone is taking ~25 hours and a vessel also has to be used to retrieve the PLR.

Option B: Displacement by flushing

This option simplifies the procedure both regarding equipment and commissioning vessel usage. This option removes the need for a pig receiver to collect the foam pigs. It also removes the risk of dissolving pigs.

4.6 Identified points of optimization and conclusion

The evaluation sheet identified the risk of less effective air evacuation. Displacement by flushing is a very lucrative option, and further calculations are performed to acknowledge the viability of the procedure.

4.6.1 Flow displacement calculation

This calculation is performed to evaluate at what velocity flushing is a viable option. To do this calculation as reliable as possible three methods of calculation is performed: The Colebrook white equation method, The Swamee-Jain equation method, and the Haaland equation method [45]. This calculation is performed to find the lowest velocity required to achieve plug flow and effective evacuation of air.

Input data	Symbol	Value	Unit
WI length (WI01+WI02)	l	46465	m
WI ID 12"	d	0.2857	m
PE-liner roughness	ϵ	0.0015	mm
Temperature	T	5	˚C
Viscocity (dynamic)	μ	1.519E-03	kg/(m*s)
Viscocity (kinematic)	ν	1.519E-06	kg/(m*s)
Pipeline cross section area	A	0.0641	m²
Density	ρ	1000	kg/m3
Velocity	v	1.21	m/s
Height difference	Δh	310	m

Table 4.6-1: *Flow calculation input*

Water injection flow calculation, input data related to pipeline material [46], liquid properties [47] and pump capacity [48].

$$Relative\ roughness = \varepsilon = \frac{\epsilon}{d}$$

Relative roughness is found by the inside wall roughness over inner diameter

$$Volume\ flow = Q = \pi * \frac{d^2}{4} * v * 3600$$

The flow is calculated to the pipeline section to represent the largest part of the pipeline.

$$Hydrostatic\ pressure = \Delta P_{hydrostatic} = p * g * \Delta h$$

Hydrostatic pressure is calculated by the height difference between inlet and outlet.

$$Re = \frac{\rho * v * \mathrm{d}}{\mu}$$

As a guideline flow is in the laminar flow region if Reynolds number is < 2100. The flow is expected to be in the turbulent region when Reynolds number is > 4000 [49], the region in between is called transition zone, and the flow profile may be unstable.

Calculations	Symbol	Value	Unit
Relative Roughness	ε	5.3E-06	mm/mm
Volume flow	Q	279	m^3/h
Hydrostatic differential pressure	Δp hydro	3041100	Pa
		30.4	bar
Reynolds number	Re	227582	

Table 4.6-2: *Reynold number calculation*

Darcy friction factor is first found by the Moody Chart for a approximated value. Further on the Colebrook white equation is used to find a more exact friction factor.

$$\frac{1}{\sqrt{f}} = -2 * LOG10[\left(\frac{\frac{\epsilon}{d}}{3.7}\right) + \left(\frac{2.51}{Re * SQRT(f)}\right)]$$

The Colebrook white equation is solved by finding a friction value to balance the equation. This is found by iteration of the two values from each side of the equation is visualized in the graph below.

f values	Part 1	Part 2
0.031	5.679618	5.648528
0.03105	5.675044	5.648565
0.0311	5.67048	5.648602
0.03115	5.665927	5.648639
0.0312	5.661385	5.648676
0.03125	5.656854	5.648713
0.0313	5.652334	5.64875
0.03135	5.647825	5.648787
0.0314	5.643326	5.648823
0.03145	5.638839	5.64886
0.0315	5.634362	5.648896
0.03155	5.629895	5.648933
0.0316	5.62544	5.648969
0.03165	5.620994	5.649005
0.0317	5.61656	5.649041
0.03175	5.612135	5.649077
0.0318	5.607722	5.649113

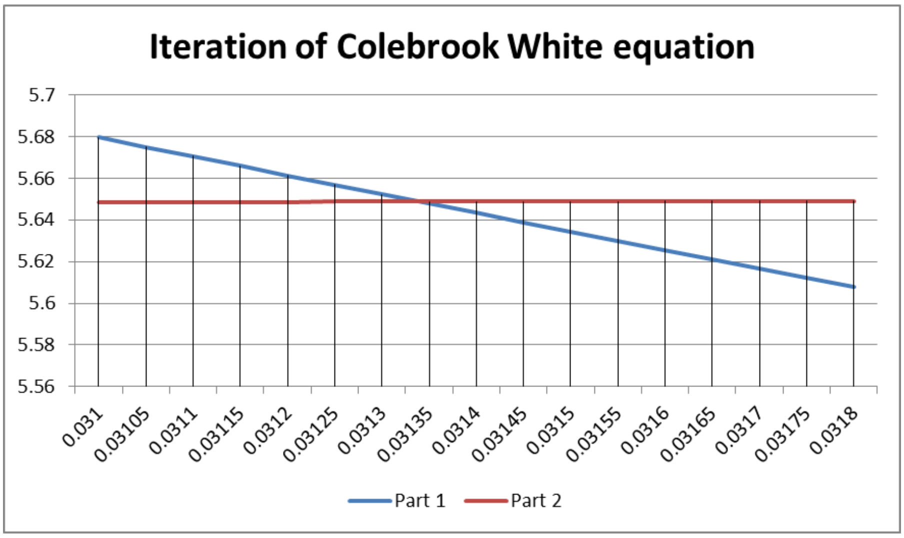


Figure 4.6-1: *Colebrook White iteration*

There are several equations to find the friction factor without the use of iteration. Two of them are used here to confirm that the Colebrook White equation is solved correctly.

$$f = 0.25 * [log_{10}\left(\frac{\in}{3.7 * d} + \frac{5.74}{re^{0.9}}\right)]^{-2}$$

The Swamee-Jain equation to find friction factor

$$\frac{1}{\sqrt{f}} = -1.8 * log_{10}\left[\left(\frac{\frac{\epsilon}{d}}{3,7}\right)^{1.11} + \frac{6.9}{Re}\right]$$

The Haaland equation to find friction factor

$$\text{Pipeline pressure loss} = \Delta P_{friction} = \frac{f * \rho * v^2 * l}{2 * d}$$

When a relative good Darcy friction factor is found, pipeline pressure loss can be found using the Darcy-Weisbach equation.

$$Shear\ force = \tau_w = \frac{\Delta P_{friction} * d}{4 * l}$$

Shear force acting on the inside pipeline wall

$$u_w = \left(\frac{\tau_w}{\rho}\right)^{0.5}$$

Friction velocity

$$\delta s = \frac{5 * v}{u_w}$$

The sublayer thickness can be calculated where v is the kinematic viscosity.

$$\delta s \ll d$$
$$0.0001 \ll 285.7$$

To predict if plug-flow is achieved, the sublayer thickness must be very small related to the inner diameter. In this calculation, 0.1mm is set as the sublayer thickness of a good developed plug flow profile.

Calculations	Symbol	Value	Unit
Darcy friction factor (Moody Chart)		0.018	
Colebrook-White equation part 1		5.645	
Colebrook-White equation part 2		5.659	
Darcy friction factor (used as basis)	f	0.0314	
Swamee-Jain equation of	f	0.0314	
Haaland equation 1/sqrt(f)=		8.12	
Haaland equation	f	0.0351	
Pipeline pressure loss	Δp friction	3736729	Pa
		37.37	bar
Shear force on the wall	τw	5.74	Pa
Friction velocity	uw	0.076	m/s
Sublayer thickness	δs	0.00010	m

Table 4.6-3: *Determination of sublayer thickness*

Calculation summary and conclusion

Of the three calculations, the Darcy and Swamee-Jain friction calculation was the most conservative by predicted the highest velocities to achieve plug flow. The velocity to achieve plug flow with a sublayer thickness of 0.1mm was calculated to be 1.21m/s. This corresponds to a flow of ~280m³/h. Plug flow is achieved at this velocity because, the low inner pipeline roughness on the PE-liner A flow table is created [Appendix B] from the calculations. The pump capacity of the SRP is implemented in [Appendix B], and note that pump 2 is found not sufficient to achieving a good plug flow profile. Pressure loss by increased velocity is also calculated to confirm the pump capacity.

$$Flushing\ duration = \frac{l}{v} = \frac{45\ 000m}{2.5m/s} \approx 5hours$$

If both SRP pumps are run together a velocity of 2.5m/s estimated to be achievable. The displacement of the complete pipeline will then take approximately 5 hours. The less effective air evacuation compared to pigging can be compensated by a longer flushing period.

If the demanded pump capacity is made available at the pipeline installation vessel, plug flow flushing may also replace foam pigging for the pre-commissioning procedure.

5 PRODUCTION SYSTEM

5.1 Pre-commissioning of the production pipeline

Pre-commissioning methodology of the production pipeline is quite similar to the gas lift pipeline since they both are pipelines with an inner metal layer. The main difference is the ILT connection installed to connect Maria template G. The pig train setup for flooding cleaning and gauging is similar to the gas lift pipeline. But the pig selected for gauging must be compatible with the ILT passing. A pig with gauging plate will not reach into the opening at the ILT like a spring loaded caliper pig or smart pig [2.3 Equipment considered in commissioning procedures]. The branch at the ILT is pre-filled with MEG and the valve at the ILT is kept closed under the pre-commissioning procedure.

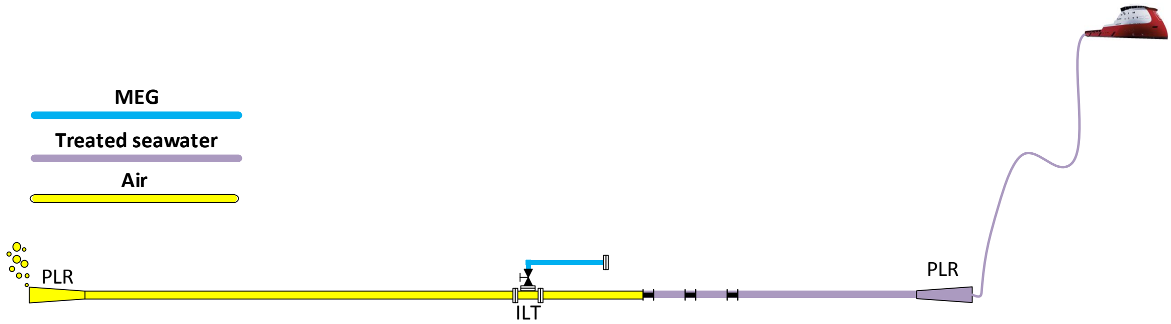


Figure 5.1-1: *Flooding, cleaning, and gauging*

Pig train is set up by a displacement pig, a cleaning pig, and a gauging pig. The procedure is performed directly after pipeline lay down.

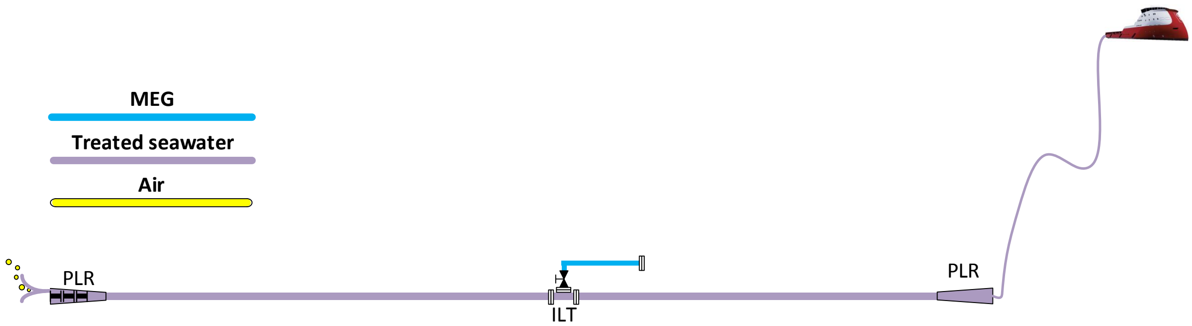


Figure 5.1-2: *Air evacuation and pressure testing*

After the three pigs are received at the PLR, Treated freshwater is flushed until air is displaced visually measured by air bubbles. The pipeline is sealed, and the pressure pumped up to 40bar (10bar above seabed pressure) to restrict seawater ingress. The pipeline is then temporary abandoned.

5.2 Production system battery limits

The physical battery limit is at the topside hang-off flange, Statoil has suggested to supply the riser or take an already in place riser in further use. All topside activities at Kristin must be executed under Statoil's approval and work management system.

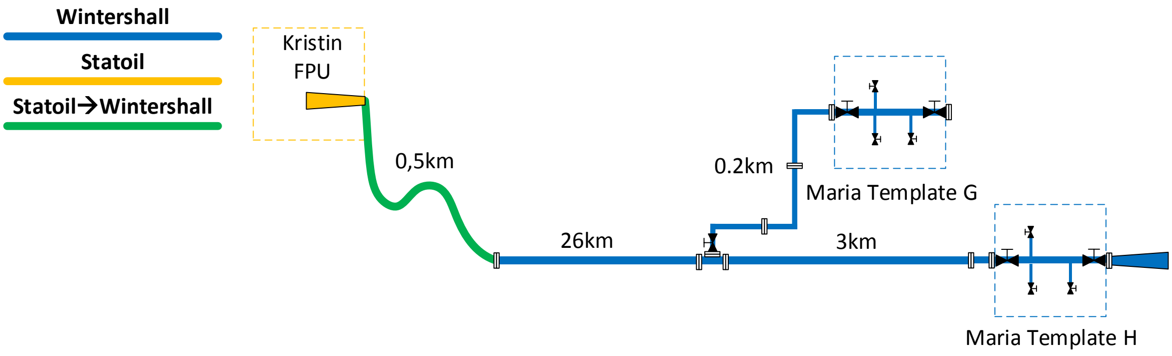


Figure 5.2-1: *Production system overview*

5.3 Considerations to commissioning strategy

Special consideration to commissioning must be taken regarding hydrate formation. This should be prevented by ensuring separation of the oil and gas safely with the treated water. However, the risk of hydrates is not as critical as with gas since oil with water at low pressure is not critical of creating hydrates. Another risk by mixing oil and water is the creation of oil emulsion. If oil and water mixes with a concentration above 20% depending on the oil, the risk of creating an oil/water slurry is considerable [50]. If emulsion occurs in large scale, it will block the pipeline.

For hydrate prevention, a direct electric heating (DEH) cable is installed on the main pipeline. The spools connecting ILT to Maria template G are not heated but are instead insulated. Under production phase, this part is planned to be displaced by MEG if production shuts down. The flow rate during commissioning is usually quite low, measures should be implemented to prevent hydrate formation during start-up of the spool connection.

The commissioning of the production pipeline will affect the production at Kristin. Any displaced fluid from the Wintershall Maria production line must be treated and discharged or produced at Kristin. Fluids used in the commissioning must be selected so that Kristin can accommodate treating of fluid related to discharges or production up sets.

5.4 Commissioning start-up

The first steps after tie-in are common to all commissioning alternatives and is first explained.

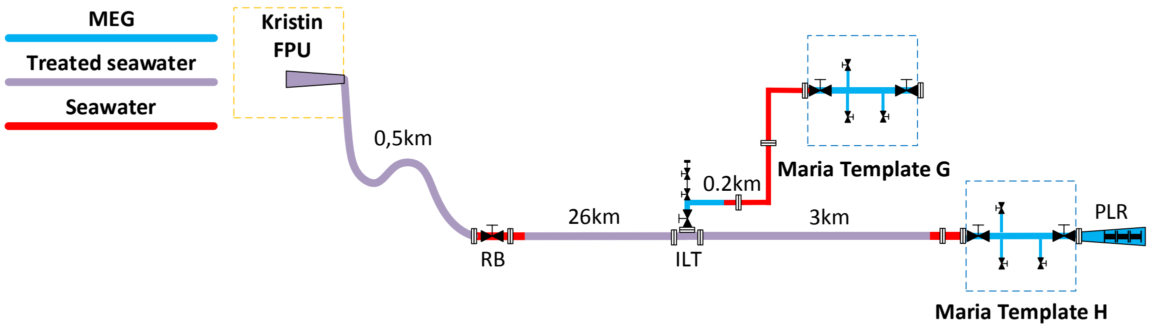


Figure 5.4-1: *Production system after tie-in procedure*

The illustration above shows the expected sea water ingress points during the tie-in procedure. The three spools connecting ILT to Maria template G is pre-lined with wax to withstand sea water for a shorter period.

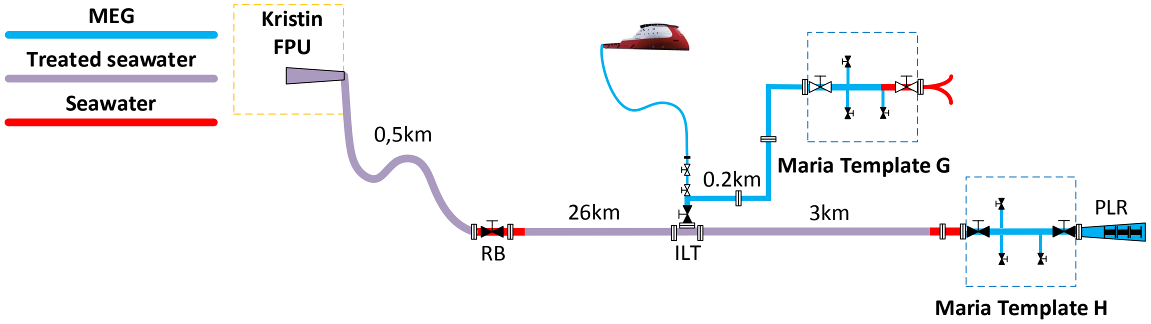


Figure 5.4-2: *ILT to Maria template G conservation*

The first operation of commissioning is to connect to the subsea connection point at the ILT branch and displace the sea water by dyed MEG. Flushing is continued for a few minutes after dyed liquid arrives at the outlet at the Maria template G. This system is then pressure tested and left pressurized at 40bar.

5.4.1 Option A – Diesel filling before start-up

The most conservative option of commissioning for the start-up procedure is pre-filling the complete pipeline with diesel. Diesel does not create any hydrate issues mixed with water. Another benefit of this option is that the diesel is not lost but can be retrieved at Kristin and mixed in the production.

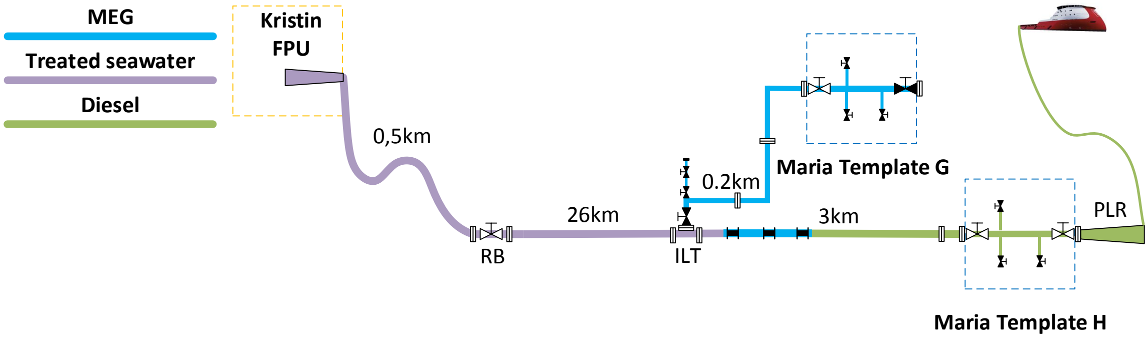


Figure 5.4-3: *Water displacement*

Two MEG slugs between three displacement pigs are suggested for the displacement operation. The commissioning vessel must be able to carry a volume of 2000m³ diesel for this operation.

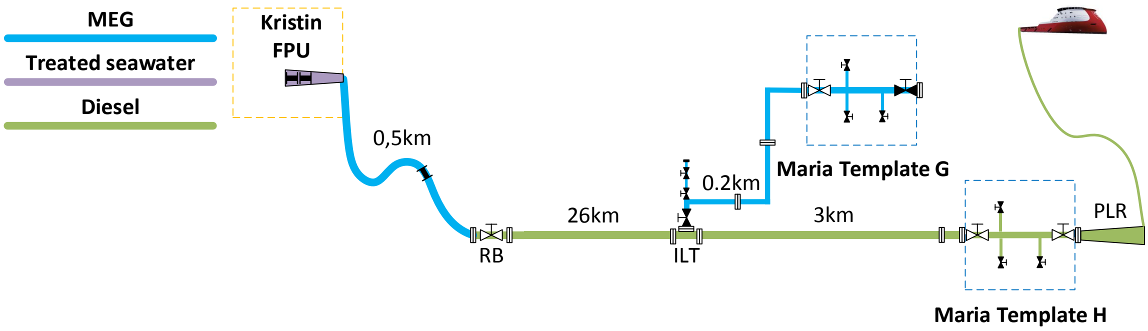


Figure 5.4-4: *Diesel filling and displacement*

At safe distance before the first pig arrives at Kristin, displacement to sea is stopped, and displaced fluid is now to enter the test separator at Kristin.

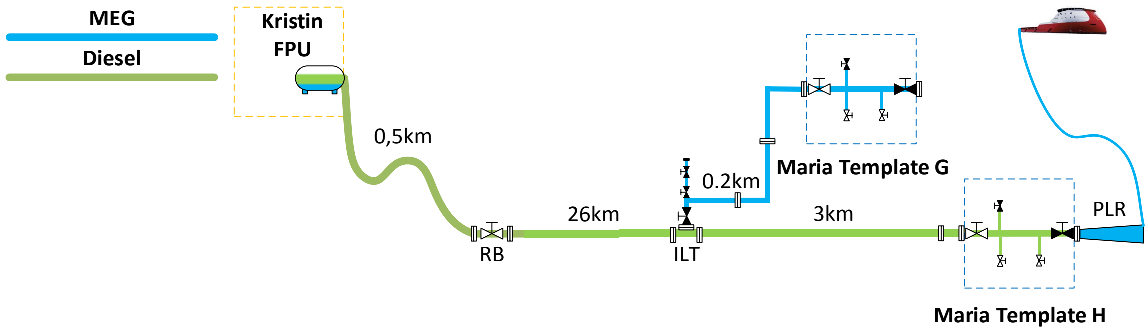


Figure 5.4-5: *Diesel filling*

The objective is to not spill hydrocarbons to sea but rather enter the production mixed with MEG. The vessel starts pumping MEG until the hose is completely displaced, and all pigs received at Kristin before disconnection. The system is now temporary abandoned until production and start-up can happen.

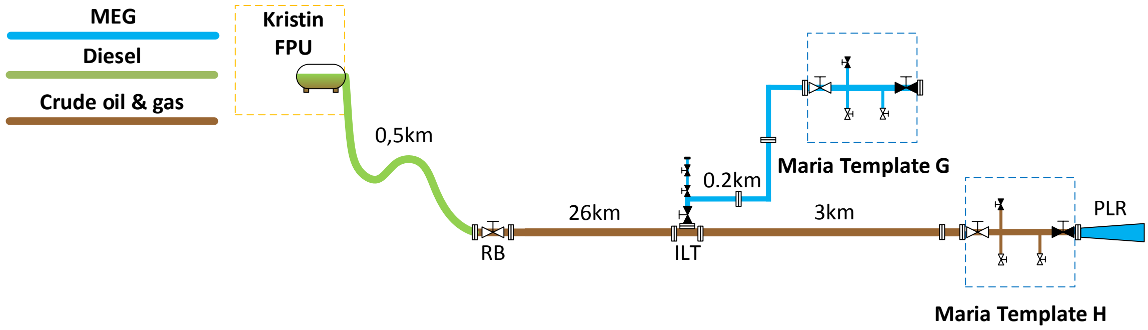


Figure 5.4-6: *Start-up Maria template H*

When two wells are ready for operation at Maria template H or G, the DEH-cable is enabled to increase the temperature above HFT (hydrate formation temperature). When the temperature at RB (riser base) reaches HFT, opening of the two first wells is performed. Slugging as a cause of gas during startup must be expected and is one of the reasons test separator is used to mitigate the process stir-up.

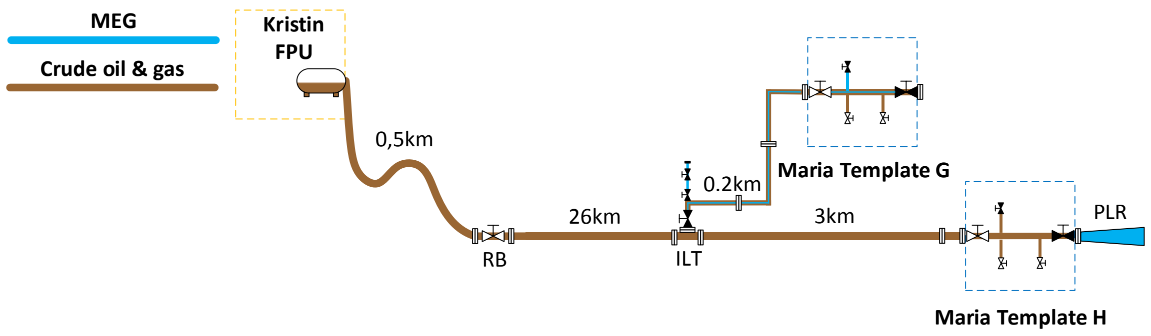


Figure 5.4-7: *Start-up of Maria template G*

After production from Maria template H has stabilized, Maria template G may start as soon as two wells are ready. During startup from Maria template G, MEG must be injected in a volume such that the mix holds an HFT lower than seabed temperature. This inhabitation must continue until the wells have stabilized, and the gas slugs reduce. Maria template G may also be started up first in this procedure, but initial start-up from Maria template H is the preferred option.

5.4.2 Option B – Diesel slug

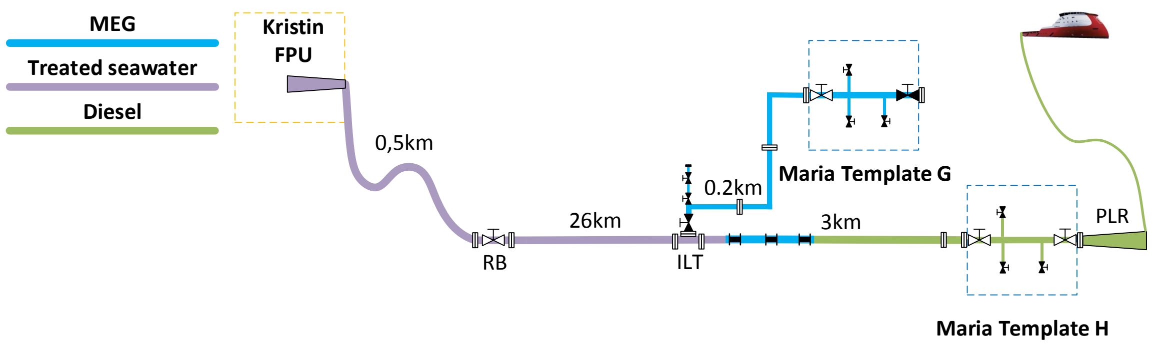


Figure 5.4-8: *Diesel slug*

A pig train of two 15m³ MEG slugs separated by three pigs first enters the system from Maria template H. The pig train is propelled by diesel until all pigs are past the ILT. The volume of injection diesel to pass the ILT is estimated to be 250m³. MEG is then injected from the vessel to displace riser hose and PLR before disconnection.

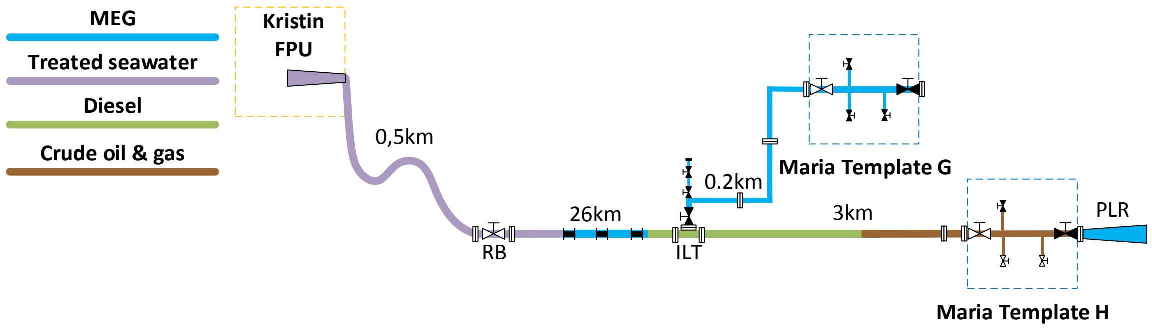


Figure 5.4-9: *Diesel slug and start-up of Maria template H*

DEH is started to reach HFT. Production is then started when two wells from Maria template H is available to drive the pig train. Choke valves at each well should be active operated to try keeping a stable pressure in between 40-60bar. The pigging velocity is adjusted at the outlet of the PLR at Kristin to keep a velocity of 0,5m/s.

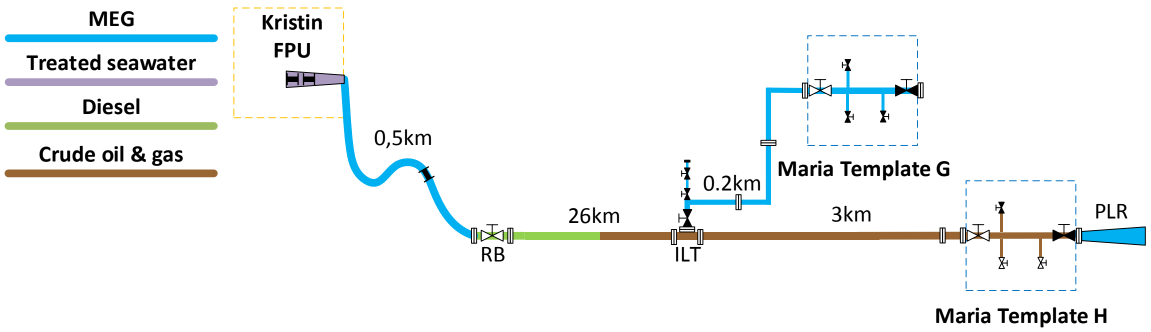


Figure 5.4-10: *Receiving pig train at Kristin*

At a safe distance before the first pig is received, displacement to sea is turned over to enter the test separator.

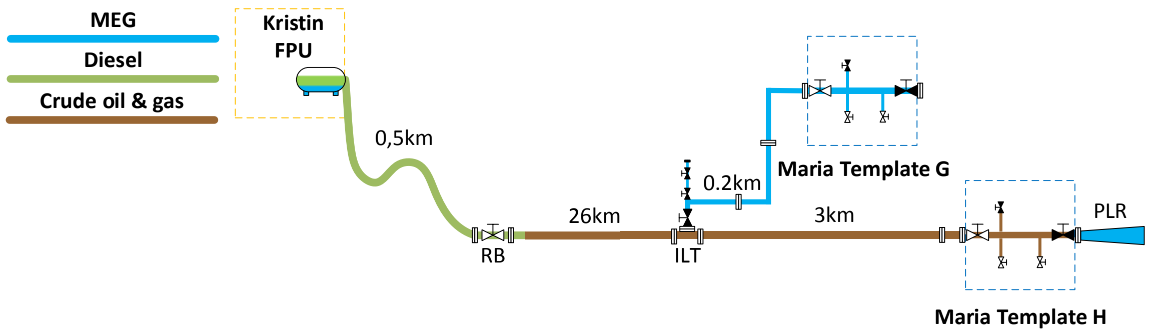


Figure 5.4-11: *Switchover to separator*

The switchover should be performed as smoothly as possible to prevent the last pigs of stopping in the riser section.

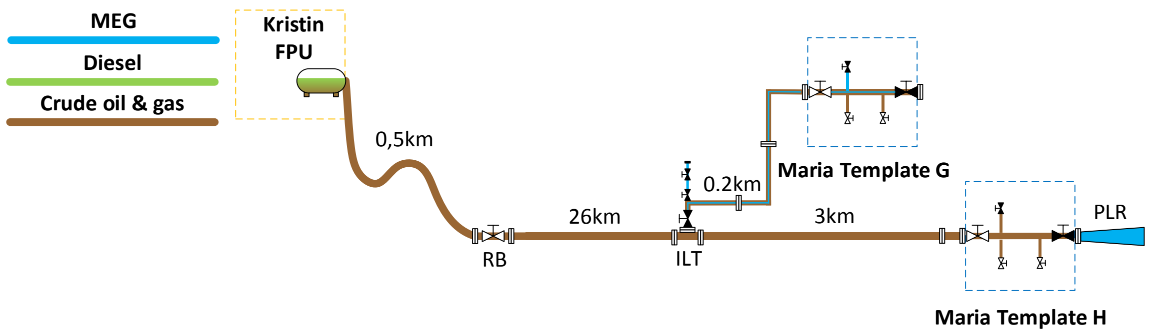


Figure 5.4-12: *Start-up of Maria template G*

Startup of Maria template G is performed with a similar procedure as described in option A.

5.4.3 Option C – MEG slug

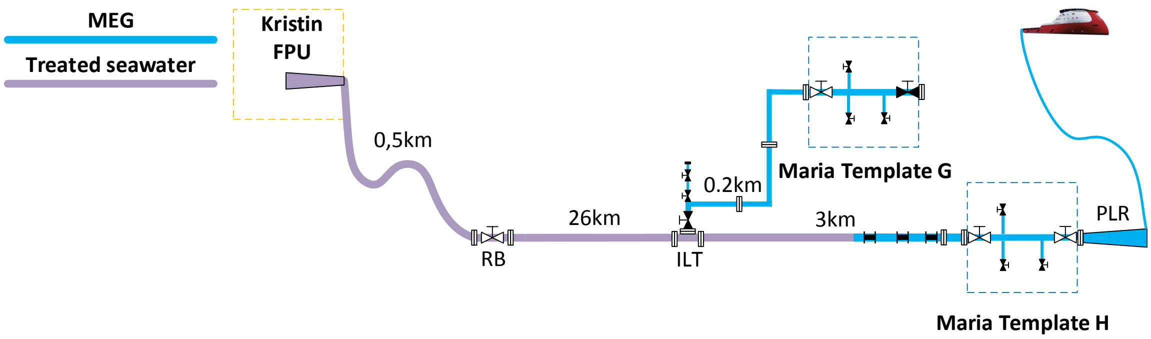


Figure 5.4-13: *Large MEG slug train*

Three MEG slugs separated by three pigs is injected from Maria template G. Total length of the pig train from first to last pig is ~1000m if three MEG slugs of 15m³ are used. This volume related to the pipe size is quite large to compensate for multi-diameter sections.

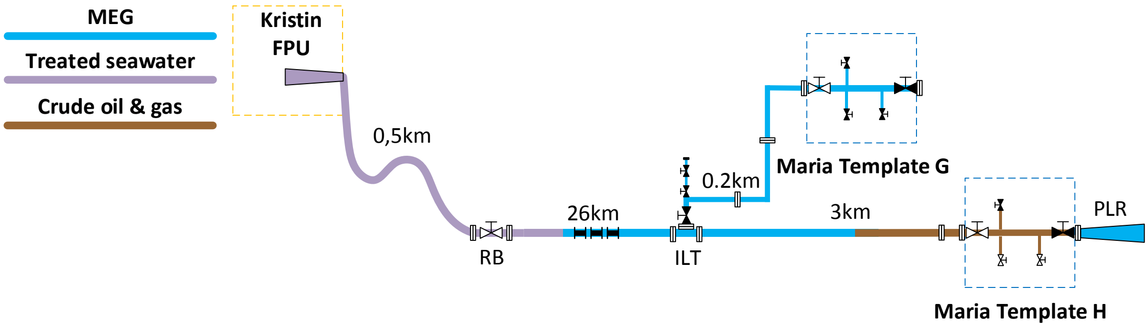


Figure 5.4-14: *Start-up of Maria template H*

The DEH system is started up to reach HFT before wells at Maria template H is opened. The critical point is in the riser at Kristin. The riser is not pre-heated and at this point it is critical that water not has mixed past the MEG slug to the hydrocarbons. At a rising pressure and decreasing temperature hydrates may be a danger to the commissioning.

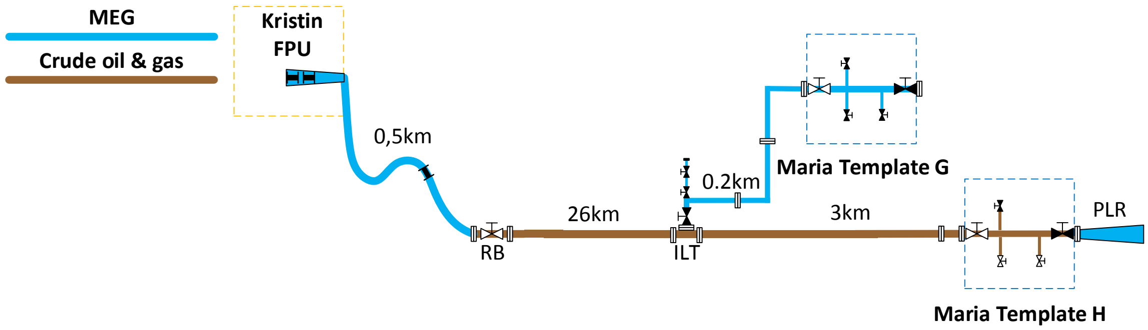


Figure 5.4-15: *Displacement by production*

To achieve a good pig-sweep, the velocity should be regulated to hold a constant velocity of 0.5m/s.

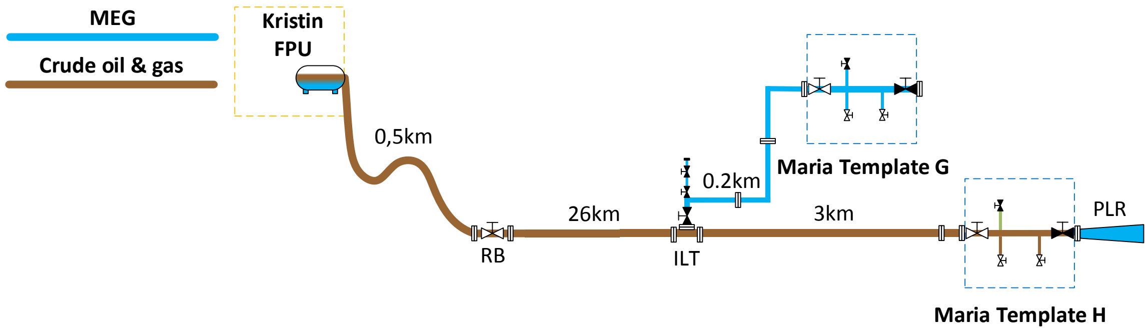


Figure 5.4-16: *Switch to separator*

Before first pig has arrived at Kristin displaced fluid is switched to test separator to enter production. A large amount of MEG must be expected to enter the test separator mixed first with water and then with hydrocarbons.

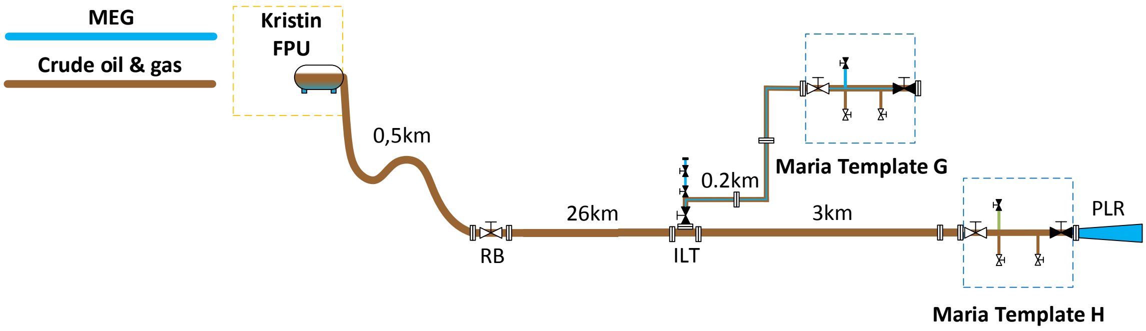


Figure 5.4-17: *Start-up of Maria template G*

When Maria template H produces without large gas slugs, Maria template G may be started similar to option A procedure.

5.4.4 Option D – Nitrogen driven pig train

This option is very much the same as option A. The idea of using nitrogen instead of diesel is to reduce cost.

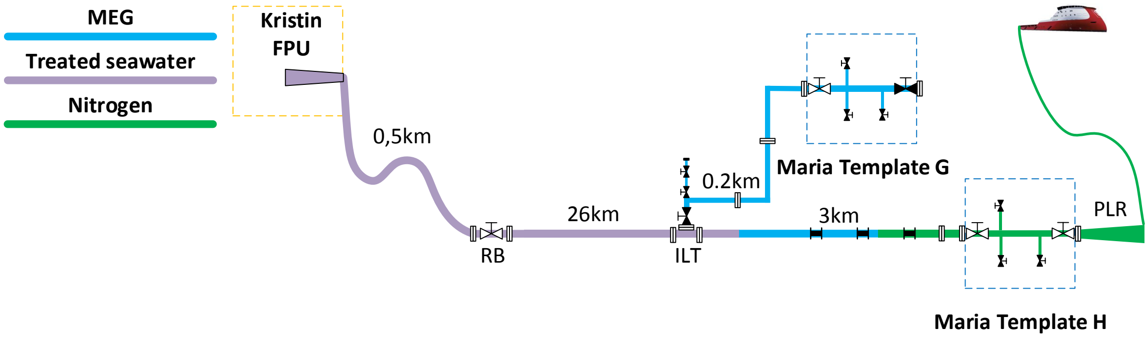


Figure 5.4-18: *Nitrogen driven pig train*

Two MEG slugs of 15m³ are injected in front and behind the first pig. 430Sm³ of nitrogen is injected in front of the last pig to sweep up residues of liquid.

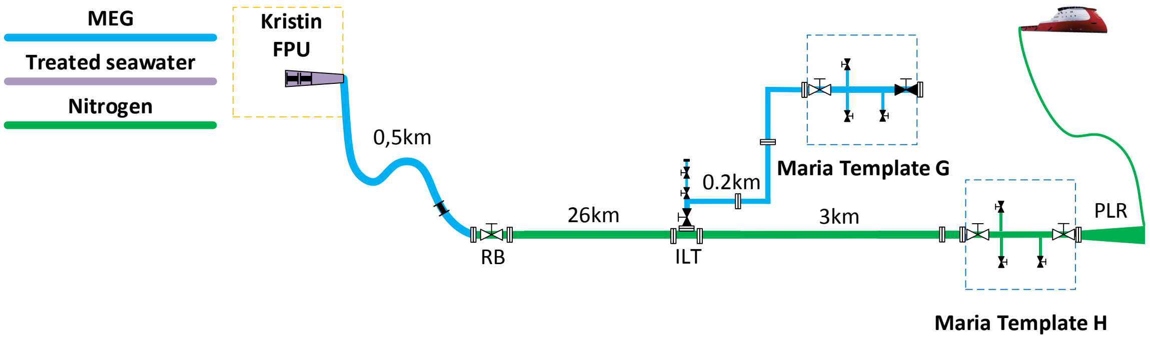


Figure 5.4-19: *MEG displacement*

The complete pipeline is displaced by nitrogen with a continuous pressure of 40bar. This procedure requires ~100 000Sm³ of Nitrogen (ten 20m³ tanks containing 16,5m³ liquefied nitrogen each) [Appendix C]. And will leave the pipeline with pressurized nitrogen of 40bar.

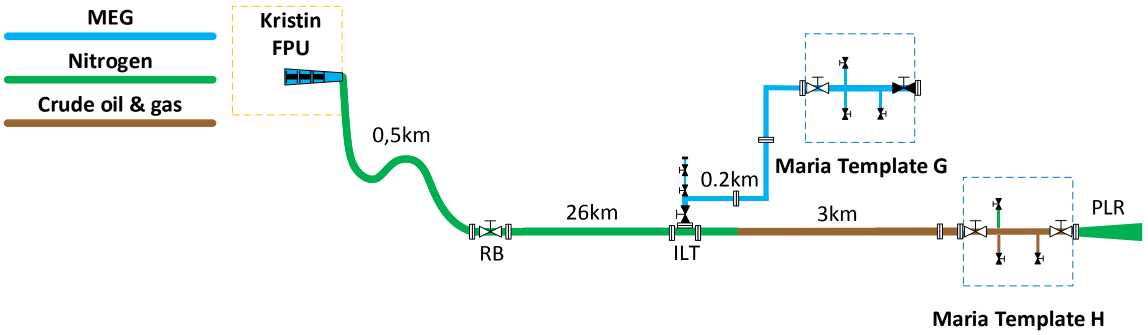


Figure 5.4-20: *Production start-up from Maria template H*

At this point, the production can be started from either Maria template H or G. Water is displaced enough to prevent a hydrate plug to form. The nitrogen collected in the pipeline must be flared at Kristin. Nitrogen is not wanted in the production and is not either an environmental issue, but the nitrogen gas should be vented to a flare together with hydrocarbon gas.

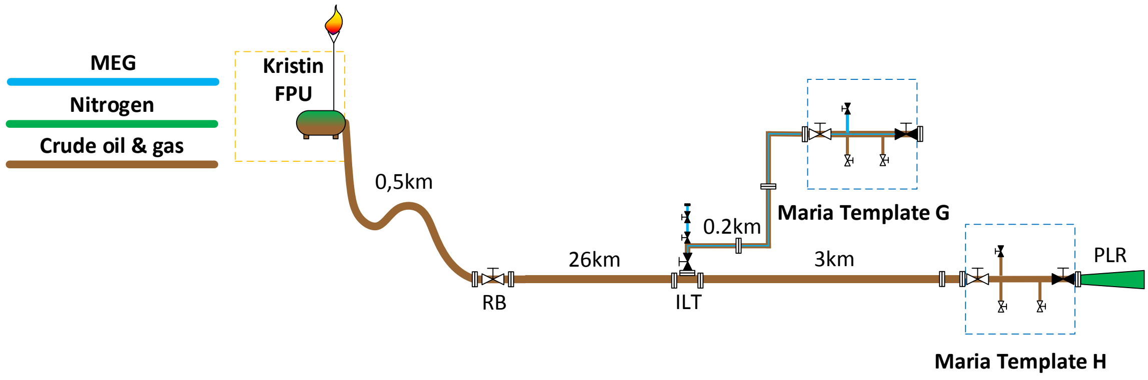


Figure 5.4-21: *Production start-up from Maria template G*

At start-up from Maria template G, MEG has to be injected until the tie-in spool section is heated up above HFT. The MEG residues are produced and expected to cause some production stir-up, but at an acceptable level.

5.4.5 Startup performed from Maria template G with diesel slug

This part is to explain the changes to the previous procedure in Option B if start-up is to be initiated from Maria template G.

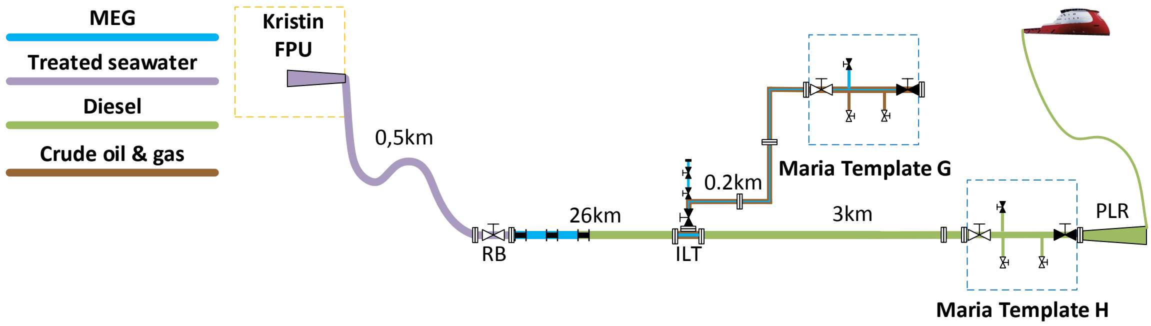


Figure 5.4-22: *Diesel to displace pig train past ILT*

The diesel slug has to be increased to 500m³ to displace the pig train 3km in front of ILT. The part back to Maria template H remains diesel filled.

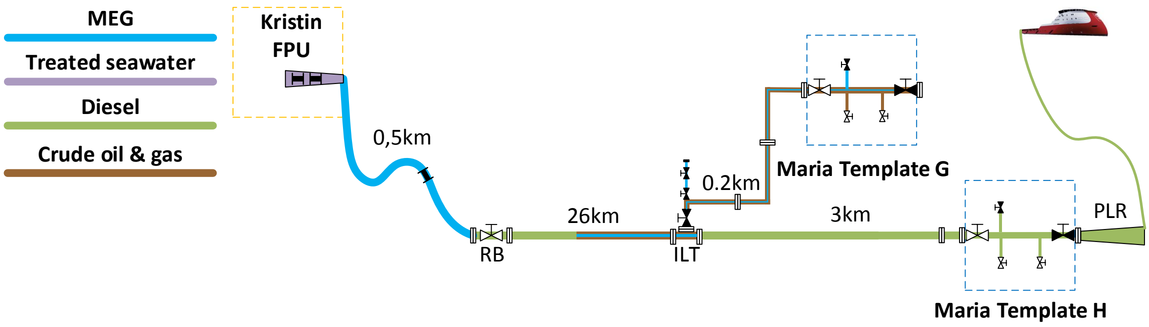


Figure 5.4-23: *Start-up Maria template G with MEG injection*

The start-up is then implemented from Maria template G with MEG injection. The pig train is then propelled by production from Maria template G.

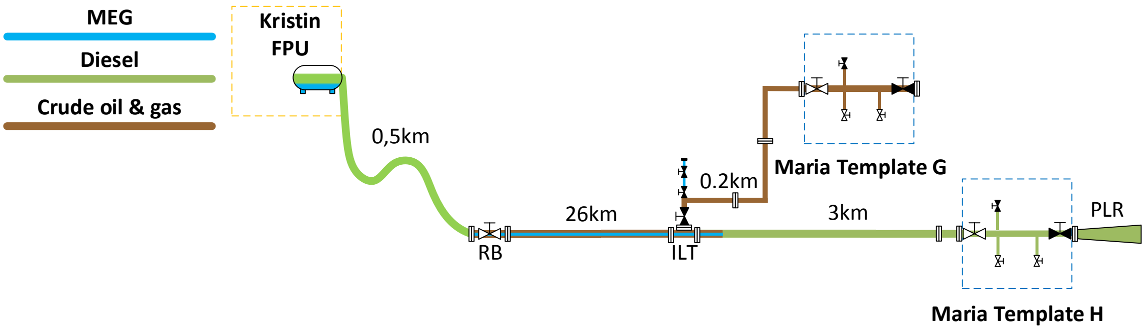


Figure 5.4-24: *Diesel to displace pig train past ILT*

Production continues from Maria template G until it is stable. Then production from Maria template H is started up.

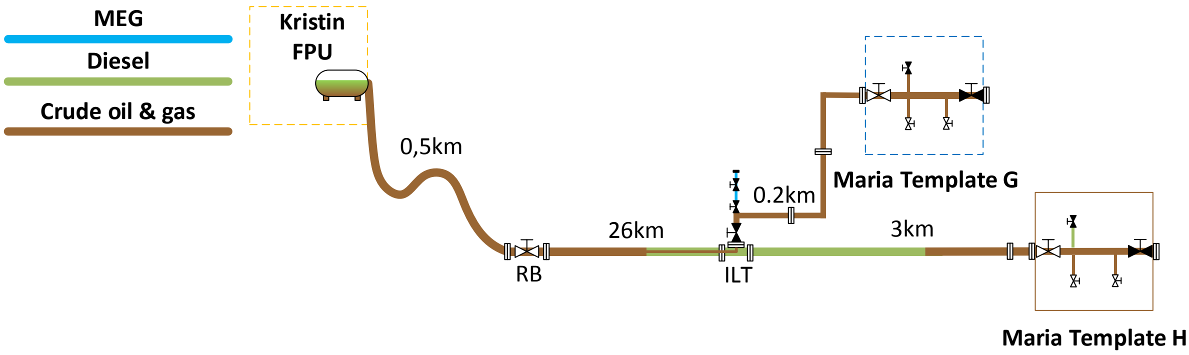


Figure 5.4-25: *Start-up of Maria template H*

When Maria template H is starting up, a process stir-up must be expected because of the 250m³ diesel slug mixing with Maria template G production.

5.5 Displacement and start-up evaluation of the production system

Area of importance	Multiplication factor	Option A : Diesel filling before start-up	Driver value A	Option B: Diesel slug	Driver value B	Option C: MEG slug	Driver value C	Option D: Nitrogen driven pig train	Driver value D
Safety to personnel in operation	1.4	Large volume and equipment handling on vessel	-1	Equipment handling on vessel	0	Equipment handling on vessel	0	Much equipment handling on vessel	-1
Environmental consideration	1.3	Small discharges	0	Small discharges	0	Some MEG discharges	-1	Nitrogen flaring	-1
Integrity of procedure	1.2	Very good integrity of procedure	2	Good integrity, but must perform displacement continuously	1	Must perform displacement continuously and only from Maria H	-2	Very good integrity of procedure	2
Interface issues to host	1.1	Expect process stir up by the large diesel volumes	-1	No large process stir up	0	Expect process stir up by the large MEG volumes	-1	Nitrogen flaring	-1
Cost	1.0	Large cost on diesel and supply vessel	-2	Reduced diesel cost	0	Low cost alternative	2	Cost both in volume and mob/demob	-1
Total evaluation sum:			**-2.1**		**1.2**		**-2.8**		**-2.4**

Figure 5.5-1: *Evaluation sheet on production start-up*

5.5.1 Summary of evaluation to displacement and production start-up

Option A: Diesel filling before start-up

This procedure is by far the most conservative, but start-up integrity is maintained at all times during the final commissioning. Hydrate formation is not possible because of the complete fluid displacement, but the cost is quite extensive because of diesel usage and transport by vessel to the injection point.

Option B: Diesel slug

This procedure reduces the volume consumption of diesel by approximately 2750m³ by only filling diesel past the ILT from Maria template H. The integrity of the procedure is good, but should not stop for longer periods during displacement. Less process stir-up are expected because of the reduction of diesel volume.

Option C: Large MEG slug

This procedure is similar to the diesel slug alternative but with smaller volume consumption. The downside is that process start-up has to be performed from the Maria template H since the pig train not is displaced past the ILT. Of all options, this is considered as the low-cost option.

Option D: Nitrogen driven pig train

This procedure is to perform a de-watering pig train procedure before production start-up. This procedure has very good integrity, and start-up is made possible from both templates. A downside of the procedure is the introduced nitrogen that requires flaring at Kristin.

5.6 Identified points of optimization and conclusion

The option of using a large MEG slug of 250m³ diesel after a pig-sweep train consisting of two 15m³ MEG slugs is evaluated as the best option. By a much less volume consumption of diesel, vessel usage cost is reduced. Stir-up of production at Kristin will also be reduced by a smaller usage of both diesel and MEG. As long as the diesel slug is injected a short period in front of the start-up, the integrity of the procedure will be satisfying. Displacement pigs should not be stored in diesel for longer periods since diesel can dissolve parts of the sealing material used in displacement pigs.

The next sections are a summation of ideas to improve the commissioning procedure and optimize further production.

5.6.1 MEG injection at Kristin riser base

By introducing MEG injection at Kristin RB in the start-up procedure, hydrate formation is prevented since the DEH does not heat up the riser section. This can be controlled by the RB temperature measurement.

5.6.2 Tie-in spool selection to Maria template G

The selected connection option to connect Maria template G to the production pipeline is three rigid spools, see [Figure 2.1.3-1] production system schematic. This section stretches in pipeline length approximately 200m and is intended insulated.

Hydrate formation in the production pipeline is the main flow assurance concern for commissioning and shutdowns. Oil combined with water and high pressure may cause hydrate formation. This effect is mitigated by high temperature or by injecting hydrate mitigating fluid (MEG is commonly used). The SPS is to be insulated to achieve 12 hours total cool down time (CDT) before hydrate formation [51]. Depressurizing and MEG inhabitation is estimated to take 6 hours. This means that no-touch time is 6 hours.

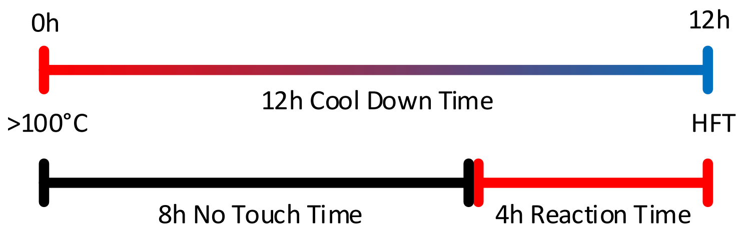


Figure 5.6-1: *Time scale towards hydrate formation*

For insulation on the SPS, Novalastic insulation with high subsea insulation qualities is used. Spools from production pipeline to Maria template G and H is insulated by a thick layer of plastic material to resist seabed dragging during installation. DEH is to be installed as piggyback cable on the production pipeline. Riser is insulated but must be MEG inhabited within CDT. DEH is powered from Kristin. DEH is a technique developed for pipeline heating by using the metal inner layer of the pipeline as the conductor in a large high voltage circuit. High voltage cable is terminated at each side of the pipeline. The first connection is by the Kristin riser base, and the second connection is provided by a piggyback cable to the pipeline end at Maria template H. This leaves only the spool to Maria template G and H to be insulated.

The rigid spool option to connect Maria template H to the ILT connection at the production pipeline is only to be insulated. These three spools in line make up in total four goose neck points. Because of this the complete section has to be displaced within the CDT. This could be improved by selecting a flexible pipeline in place of the three rigid spools, and the section would only need MEG injection. The length of the section will also be drastically improved because the flexible pipe not will need stress reduction bends.

5.6.3 Production phase

Kristin production unit will become the daily operator of the Maria SPS. On behalf of Wintershall, the main concern to flow assurance is hydrate formation. Oil samples of the Maria crude were analyzed, and hydrate formation is the main concern. Waxing will not be a problem, but scale and asphaltene might occur during production. Scale inhibitor and asphaltene dispergant will be injected at each producing well. Acoustic sand detectors are installed at all producing wells to mitigate erosion by early detection. The pipeline route is assessed, and points for rock dumping are located for leveling of the seabed. This is for the mitigation of terrain slugging. Maria is a high pressure and high temp reservoir, so flow velocity should be in the turbulent zone in the designed 10-inch production pipeline. For the water injection line, corrosion is a concern. For mitigation, this line is to be plastic lined.

6 ESTIMATED CHEMICAL USE TO THE SELECTED PROCEDURES

As a summary, the total consumption of chemicals is listed to give a better picture of total chemical usage in commissioning of the pipelines to the Maria development.

6.1 Gas lift commissioning

Chemical	Volume	Unit	Purpose	Comment
Treated seawater	**355**	**m^3**	Pre-commissioning	1.1x volume
TEG	**14.7**	**m^3**	For use in pig sweep slugs	
	17	m^3	Pig train displacement	
	15	m^3	Drying of pipeline	
	152	m^3	Pressurization	
Liquid nitrogen	**184**	**m^3**		
	1.5	m^3	Pre-filling of manifolds	
	4.7	m^3	Flushing of PLEM	1.1x volume
MEG	**6.2**	**m^3**		

Table 6.1-1: *Gas lift chemicals*

6.2 Water injection commissioning

Chemical	Volume	Unit	Purpose	Comment
Treated seawater	**3833**	**m^3**	Pre-commissioning	1.1x volume
Water for injection (SRP)	**3833**	**m^3**	Pig-displacement and flushing	
MEG	**3.6**	**m^3**	Pre-filling of manifolds	

Table 6.2-1: *Water injection chemicals*

6.3 Production system commissioning

Chemical	Volume	Unit	Purpose	Comment
Treated freshwater	**2130**	**m^3**	Pre-commissioning	1.1x volume
	4.9	m^3	Pre-filling of manifolds	
	3	m^3	Pre-filling of ILT spool	
	9.7	m^3	Flushing spools to template G	1.1x volume
	30	m^3	For use in pig sweep slugs	
MEG	**47.6**	**m^3**		
Diesel	**250**	**m^3**	Start-up from template H	
	500	m^3	Optional start-up from template G	

Table 6.3-1: *Production system chemicals*

7 DISCUSSION

Throughout the thesis, different methods of commissioning have been identified. All methods have been evaluated against one or several options. The options found not to be suitable for the Maria pipeline systems may be suited for commissioning procedures elsewhere. With different boundary conditions, the outcome of selected commissioning method could be quite different. The Maria subsea system may not be commissioning the way suggested in this thesis, but concludes with a recommended method of commissioning to the pipeline systems.

Gas lift system

For the de-watering part of the gas lift pipeline system, a pig train separated with TEG slugs is calculated to be sufficient to reduce the water content to the required level. Because of the liquid residues left in the pipeline and no possibility to confirm the pipeline dryness, nitrogen purging is suggested as a last part of the de-watering procedure. The pig train should consist of in total five pigs. The first four are separated by three slugs of 4.9m³ TEG. The last pig should be separated by a minimum of 92.4Sm³ nitrogen to give the branches of each XT time to drain. Increasing the nitrogen volume will benefit the draining time.

The tie-in connection to Tyrihans and pressurization of the gas lift system depends on the condition of valve-51 Figure 3.8-3 (the barrier toward the Tyrihans gas lift pipeline). If this valve proves to seal sufficiently, the connection can be made. The Tyrihans GL PLEM is selected to be TEG flushed and nitrogen dried. The complete gas pipeline system is pressurized with nitrogen to equalize the pressure over valve-51. If operation-pressure must be maintained at the Tyrihans gas lift pipeline, the required injected volume corresponds to 152m³ liquid nitrogen. The nitrogen must be heated and pressurized before injection by a compressor unit. When pipeline pressure is equalized, Valve-51 is opened, and production can be started. The first produced gas will contain much nitrogen and must be flared at Kristin until the gas meets export specification.

Water injection system

Because of the low inner pipeline roughness on the PE-liner, plug flow was found achievable at the velocity of 0.95m/s this correspond to a flow of 220m³/h. Because of the large distance from Heidrun TLP to the Maria templates pressure loss has been calculated in Table 9.2-1 to evaluate pump capacity. Both pumps at the SRP are capable of achieving plug flow. If both pumps are run together a velocity of 2.5m/s (575m³/h) is achievable, and the friction pressure loss will be 195bar. The displacement of the complete pipeline will then take approximately 5 hours. Longer flushing periods reduce trapped air gathered.

If the required pump capacity is made available at the pipeline installation vessel, plug flow flushing may also replace foam pigging for the pre-commissioning procedure.

Production system

A pig train of three pigs displaced with slugs of 15m³ MEG is selected to start at Maria template H. Following the pig train a diesel slug of 250m³ should be used for final commissioning and production start-up. This slug is long enough to reach the in-line tee connection to Maria template G. If the start-up is to be performed from Maria template G the diesel slug must be increased to 500m³. The displaced water is first discharged directly to sea, and at a safe distance of the first pig arrival displaced fluid is switched over to the test separator. MEG, diesel, and produced hydrocarbons enter the Kristin test separator and then mix with other production.

TEG is evaluated to be the best chemical for de-watering purposes based on efficiency, but regarding the high cost of TEG mean MEG is selected for the de-watering slugs. Small amounts of water residues are not an issue to the production pipeline as long as there is no possibility of hydrate formation to block the pipeline. Gel can beneficially be injected in front of the pig train to increase the sealing effect on the multi-diameter section. If gel injection can have a negative effect on the selected multi-diameter pig, gel injection should be discarded, and the MEG slug increased.

Further work

Detailed engineering and testing are advised if these methods of commissioning are selected. A test of the selected pigs for the multi-diameter pigging on the production line should be performed to ensure good sealing effect. The multi-diameter pig should also be tested to have sufficient flexibility with memory to be stored compressed in the PLR.

8 CONCLUSION

The commissioning method for Wintershall’s Maria subsea pipeline system is identified in this thesis. The commissioning method selected will maintain the integrity of all systems and protect the environment from dangerous and toxic discharges. The safety and cost of commissioning are improved by reducing commissioning time and chemical usage.

Gas lift system

Selected de-watering method for the gas lift system is a combination of pig-sweeping and nitrogen drying. The pig-sweep method is an effective de-watering method and the nitrogen drying is measurable and provides a method to achieve the specified gas dew point rates.

Pressurization of the gas lift pipeline is performed using nitrogen. This volume of nitrogen will be used as a lift gas. The gas is separated from the liquids at Kristin and flared until the concentration is low enough to export.

Water injection system

After installation air removal from the pipeline by direct flushing with SRP-water has been confirmed feasible by calculation. There are two pumps at Heidrun TLP and, both have the capacity to flush the system with sufficient flow rate to achieve plug flow. Both pumps are suggested to be used to ensure as high a flow as possible and increase the effectiveness of the air removal.

Production system

The identified method of commissioning is a pig train separating MEG slugs followed by a diesel slug. The MEG slugs and pigs prevent water and diesel mixing, and the diesel slug prevents hydrate formation by mixing with the last water residues. The diesel can be recovered as a part of the production at Kristin. This method reduces the amount of MEG compared to the studied alternatives and minimizes hydrate risk for the operation.

9 APPENDIX

9.1 Appendix A: Water residues by pig train sweep

Åsgard export requirements on water residues: 0,0374 g/Sm³.

TEG slug volume [m^3]	TEG slug length [m]	One slug results in residual water content of : [g/m^3]	Two slugs results in residual water content of : [g/m^3]	Three slugs results in residual water content of : [g/m^3]	Four slugs results in residual water content of : [g/m^3]
1	73.41	17.9445	8.4848	4.0119	1.8970
1.05	77.08	17.0900	7.6960	3.4657	1.5607
1.1	80.75	16.3132	7.0123	3.0142	1.2957
1.15	84.42	15.6039	6.4158	2.6379	1.0846
1.2	88.09	14.9537	5.8922	2.3217	0.9148
1.25	91.76	14.3556	5.4303	2.0541	0.7770
1.3	95.43	13.8035	5.0206	1.8261	0.6642
1.35	99.10	13.2922	4.6556	1.6306	0.5711
1.4	102.77	12.8175	4.3290	1.4621	0.4938
1.45	106.44	12.3755	4.0356	1.3160	0.4291
1.5	110.11	11.9630	3.7710	1.1887	0.3747
1.55	113.78	11.5771	3.5317	1.0774	0.3287
1.6	117.45	11.2153	3.3144	0.9795	0.2895
1.65	121.12	10.8755	3.1166	0.8931	0.2559
1.7	124.79	10.5556	2.9359	0.8166	0.2271
1.75	128.46	10.2540	2.7706	0.7486	0.2023
1.8	132.13	9.9692	2.6188	0.6879	0.1807
1.85	135.80	9.6997	2.4791	0.6336	0.1619
1.9	139.47	9.4445	2.3504	0.5849	0.1456
1.95	143.14	9.2023	2.2314	0.5411	0.1312
2	146.81	8.9722	2.1212	0.5015	0.1186
2.05	150.48	8.7534	2.0190	0.4657	0.1074
2.1	154.16	8.5450	1.9240	0.4332	0.0975
2.15	157.83	8.3463	1.8356	0.4037	0.0888
2.2	161.50	8.1566	1.7531	0.3768	0.0810
2.25	165.17	7.9753	1.6760	0.3522	0.0740
2.3	168.84	7.8020	1.6039	0.3297	0.0678
2.35	172.51	7.6360	1.5364	0.3091	0.0622
2.4	176.18	7.4769	1.4731	0.2902	0.0572
2.45	179.85	7.3243	1.4135	0.2728	0.0527
2.5	183.52	7.1778	1.3576	0.2568	0.0486
2.55	187.19	7.0371	1.3049	0.2420	0.0449
2.6	190.86	6.9017	1.2552	0.2283	0.0415
2.65	194.53	6.7715	1.2082	0.2156	0.0385
2.7	198.20	6.6461	1.1639	0.2038	0.0357
2.75	201.87	6.5253	1.1220	0.1929	0.0332
2.8	205.54	6.4087	1.0822	0.1828	0.0309
2.85	209.21	6.2963	1.0446	0.1733	0.0288
2.9	212.88	6.1878	1.0089	0.1645	0.0268
2.95	216.55	6.0829	0.9750	0.1563	0.0250
3	220.22	5.9815	0.9428	0.1486	0.0234
3.05	223.89	5.8834	0.9121	0.1414	0.0219
3.1	227.56	5.7885	0.8829	0.1347	0.0205
3.15	231.23	5.6967	0.8551	0.1284	0.0193
3.2	234.90	5.6077	0.8286	0.1224	0.0181
3.25	238.57	5.5214	0.8033	0.1169	0.0170
3.3	242.24	5.4377	0.7791	0.1116	0.0160
3.35	245.91	5.3566	0.7561	0.1067	0.0151
3.4	249.58	5.2778	0.7340	0.1021	0.0142
3.45	253.25	5.2013	0.7129	0.0977	0.0134
3.5	256.93	5.1270	0.6926	0.0936	0.0126

Table 9.1-1: *Residual water content after TEG slugs (Part 1)*

TEG slug volume [m^3]	TEG slug length [m]	One slug results in residual water content of : [g/m^3]	Two slugs results in residual water content of : [g/m^3]	Three slugs results in residual water content of : [g/m^3]	Four slugs results in residual water content of : [g/m^3]
3.55	260.60	5.0548	0.6733	0.0897	0.0119
3.6	264.27	4.9846	0.6547	0.0860	0.0113
3.65	267.94	4.9163	0.6369	0.0825	0.0107
3.7	271.61	4.8499	0.6198	0.0792	0.0101
3.75	275.28	4.7852	0.6034	0.0761	0.0096
3.8	278.95	4.7222	0.5876	0.0731	0.0091
3.85	282.62	4.6609	0.5724	0.0703	0.0086
3.9	286.29	4.6012	0.5578	0.0676	0.0082
3.95	289.96	4.5429	0.5438	0.0651	0.0078
4	293.63	4.4861	0.5303	0.0627	0.0074
4.05	297.30	4.4307	0.5173	0.0604	0.0071
4.1	300.97	4.3767	0.5047	0.0582	0.0067
4.15	304.64	4.3240	0.4927	0.0561	0.0064
4.2	308.31	4.2725	0.4810	0.0542	0.0061
4.25	311.98	4.2222	0.4697	0.0523	0.0058
4.3	315.65	4.1731	0.4589	0.0505	0.0055
4.35	319.32	4.1252	0.4484	0.0487	0.0053
4.4	322.99	4.0783	0.4383	0.0471	0.0051
4.45	326.66	4.0325	0.4285	0.0455	0.0048
4.5	330.33	3.9877	0.4190	0.0440	0.0046
4.55	334.00	3.9438	0.4098	0.0426	0.0044
4.6	337.67	3.9010	0.4010	0.0412	0.0042
4.65	341.34	3.8590	0.3924	0.0399	0.0041
4.7	345.01	3.8180	0.3841	0.0386	0.0039
4.75	348.68	3.7778	0.3761	0.0374	0.0037
4.8	352.35	3.7384	0.3683	0.0363	0.0036
4.85	356.02	3.6999	0.3607	0.0352	0.0034
4.9	359.70	3.6621	0.3534	0.0341	0.0033
4.95	363.37	3.6252	0.3463	0.0331	0.0032
5	367.04	3.5889	0.3394	0.0321	0.0030
5.05	370.71	3.5534	0.3327	0.0312	0.0029
5.1	374.38	3.5185	0.3262	0.0302	0.0028
5.15	378.05	3.4844	0.3199	0.0294	0.0027
5.2	381.72	3.4509	0.3138	0.0285	0.0026
5.25	385.39	3.4180	0.3078	0.0277	0.0025
5.3	389.06	3.3858	0.3021	0.0269	0.0024
5.35	392.73	3.3541	0.2964	0.0262	0.0023
5.4	396.40	3.3231	0.2910	0.0255	0.0022
5.45	400.07	3.2926	0.2857	0.0248	0.0022
5.5	403.74	3.2626	0.2805	0.0241	0.0021
5.55	407.41	3.2332	0.2755	0.0235	0.0020
5.6	411.08	3.2044	0.2706	0.0228	0.0019
5.65	414.75	3.1760	0.2658	0.0222	0.0019
5.7	418.42	3.1482	0.2612	0.0217	0.0018
5.75	422.09	3.1208	0.2566	0.0211	0.0017
5.8	425.76	3.0939	0.2522	0.0206	0.0017
5.85	429.43	3.0674	0.2479	0.0200	0.0016
5.9	433.10	3.0414	0.2437	0.0195	0.0016
5.95	436.77	3.0159	0.2397	0.0190	0.0015
6	440.44	2.9907	0.2357	0.0186	0.0015

Table 9.1-2: *Residual water content after TEG slugs (Part 2)*

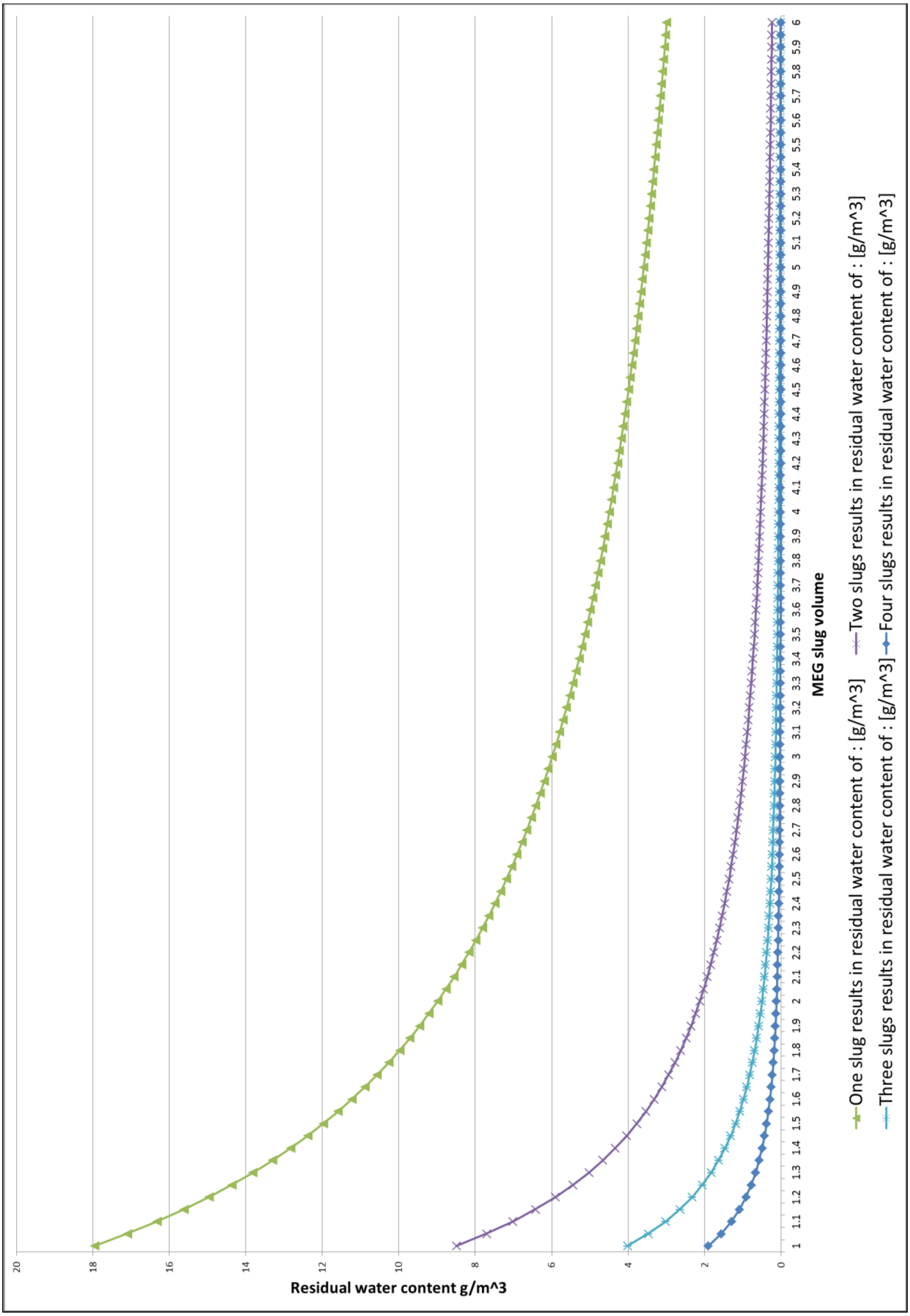


Figure 9.1-1: *Residual water content after slugs*

9.2 Appendix B: Flow regime table to the water injection line

The calculated pump requirements of the water injection commissioning are presented in Table 9.2-1. The table is divided into sections by color coding depending on the calculated sublayer thickness (δs). The red section is a too low velocity to achieve plug flow ($\delta s > 1mm$). The yellow section is good plug flow ($1mm > \delta s > 0.5mm$), but extensive flushing must be expected. The green section is very good plug flow ($\delta s < 0.5mm$) flushing velocity. Expected pumping capacity of pump one and two in the SRP is noted in the table. Pressure is not a challenge to the water injection pumps, but the volume limit of each pump restricts the maximum flow. Pump 1 is limited to 470m³/h and pump 2 is limited to 275 m³/h [52]. The combined pump capacity is estimated by combined flow volume and the capacity to meet pressure requirement.

Velocity [m/s]	Sublayer thickness [mm]	Head loss + hydrostatic pressure [bar]		Volume flow [m³/h]	Volume flow [l/min]
0.1	1.2		35.3	23.1	384.6
0.2	0.61		36.0	46.2	769.3
0.3	0.40		37.3	69.2	1153.9
0.4	0.30		39.1	92.3	1538.6
0.5	0.24		41.4	115.4	1923.2
0.6	0.20		44.2	138.5	2307.9
0.7	0.17		47.5	161.6	2692.5
0.8	0.15		51.3	184.6	3077.2
0.9	0.13		55.7	207.7	3461.8
1	0.12		60.5	230.8	3846.5
1.1	0.11		65.9	253.9	4231.1
1.2	0.10	**Pump 2 capacity**	**71.7**	276.9	4615.8
1.3	0.09		78.1	300.0	5000.4
1.4	0.09		85.0	323.1	5385.0
1.5	0.08		92.4	346.2	5769.7
1.6	0.08		100.3	369.3	6154.3
1.7	0.07		108.8	392.3	6539.0
1.8	0.07		117.7	415.4	6923.6
1.9	**0.06**	**Pump 1 capacity**	**127.0**	**438.5**	**7308.3**
2	0.06		137.1	461.6	7692.9
2.1	0.06		147.6	484.7	8077.6
2.2	0.06		158.5	507.7	8462.2
2.3	0.05		170.0	530.8	8846.9
2.4	0.05		182.0	553.9	9231.5
2.5	0.05		194.5	577.0	9616.2
2.6	0.05		207.5	600.0	10000.8
2.7	0.04		221.1	623.1	10385.5
2.8	0.04		235.1	646.2	10770.1
2.9	0.04		249.6	669.3	11154.7
3	0.04	**Combined Pump capacity**	**264.4**	692.4	11539.4
3.1	0.04		280.3	715.4	11924.0
3.2	0.04		296.3	738.5	12308.7
3.3	0.04		312.9	761.6	12693.3
3.4	0.04		330.0	784.7	13078.0
3.5	0.03		347.6	807.8	13462.6

Table 9.2-1: *Calculated flow requirement for water injection pumps to commissioning*

9.3 Appendix C: Nitrogen calculations

Nitrogen density is: 1.2506 kg/m³ at standard temp and pressure (0˚C, 1 atm) [53]
Liquid nitrogen density is: 808.4 kg/m³ (-195.8˚C, 1 atm)
Assumed ambient temperature is: 0˚C

$$V_{Gas} = P_{pipeline} * V$$

Gas volume calculation

$$V_{N2\ liquid} = \frac{V * P * \rho_{N2(gas)}}{\rho_{N2(liquid)}}$$

Liquid nitrogen calculation

Nitrogen pressurization of gas lift system

Required pressure	309 bar
System volume	4.3 m³
Reguired gas volume	99 668 Sm³
Required volume liquid nitrogen	152m³

Nitrogen for pig displacement on the gas lift system

Required pressure	40 bar
System volume	318 m³
Reguired gas volume	12 730 Sm³
Required volume liquid nitrogen	19.7 m³

Nitrogen pressurization of gas lift PLEM and spool

Required pressure	309 bar
System volume	318 m³
Reguired gas volume	1 332 Sm³
Required volume liquid nitrogen	2.1 m³

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