BERGERMEER UGS AUDIT

FINAL

REPORT

K&H

KLIMA & HEINEMANN OIL GMBH

FOR

TAQA ONSHORE B.V.

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A draft of this report was discussed during a meeting with TAQA, HEP and K&H Oil at the end of this study. During this meeting, TAQA informed K&H about ongoing work. In this report, this information is marked with the Phrase "TAQA informed K&H …".

The information received during that meeting was not checked by K&H Oil.

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Legend

Units

Length	ft	=	0.3048 m
Inch	in	=	0.0254 m
Area	acre	=	4046.86 m2
Volume	ft³	=	0.028317 m3
Barrel	bbl	=	0.159 m3
Density	lb/ft³	=	16.0185 kg/m3
API		=	141500/(API+131.5) kg/m3
Pressure	bar	=	1.00E+05 Pa
bar		=	14.50377 psi
psi		=	6894.76 Pa
Viscosity	cP	=	1.00E-03 Pas
Permeability	D	=	9.87E-13 m2
IFT	dyne/cm	=	1.00E-03 N/m
Temperature	°F	=	(°F-32)*5/9°C

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Nomenclature and abbreviations

bbl	Barrel
BER	Bergen
BGM	Bergermeer
BHP	Bottomhole pressure
bpd	Barrels per day
B_w	Formation volume factor for water
B_{wi}	Initial formation volume factor for water
c_f	Formation (rock) compressibility
CPOR	Core porosity
Dit	Tubing diameter
DRHO	density correction log
EOS	Equation of state
FF	Full field
g	Earth’s gravity
GRT	Groet
h	thickness
HEP	Horizon Energy Partners B.V.
IPR	Inflow performance relationship
k	Permeability
kh	Permeability-height product
KHOR	Horizontal permeability
KVER	Vertical permeability

MB	material balance
MD	Measured well depth
μ_w	Water viscosity
NTG	Net-to-gross ratio
OGIP	Original oil in place
OWIP	Original water in place
p	Pressure
PHIE	Log-derived effective porosity
PI	Productivity index
p_i	Initial reservoir pressure
p_r	Reservoir pressure
p_{ravr}	Average reservoir pressure
PVT	Pressure-Volume-Temperature
p_{wf}	Bottomhole flowing pressure
r_e	Drainage radius
RHOB	Formation bulk density
RQI	Rock Quality Index
r_w	Well radius
ρ_w	Water density
SBHP	Static bottomhole pressure
SGS	Sequential Gaussian simulation
SIS	Sequential Indicator simulation
SIT	Summer Injection Test

SS	Sub Sea
St	Total skin
TVD	true vertical depth
T_i	Initial temperature
UGS	underground gas storage
VFP	Vertical flow performance
Vshale	Volume of Shale
W	OWIP
Wp	Cumulative water produced
Z	gas deviation factor

BERGERMEER UGS AUDIT

1 Summary

Taqa Energy contracted K&H to perform a 5 week audit on a part of the study that is ongoing regarding the Bergermeer Underground Gas Storage (UGS) project. This audit includes geological, geophysical, well testing and reservoir engineering/simulation studies.

K&H had 2 main tasks:

1. Check, if the mentioned studies were sufficient to be in accordance with the corresponding European Norm – EN 1918-2
2. Suggest additional/different investigations, ensuring that the Bergermeer studies meet Best-Practice requirements.

The corresponding data was provided by Taqa by means of an FTP server and is described in detail in Chapter 2.2.

The results of the 5 week audit are described in detail in this final report. The main findings, according to the 2 main tasks are:

The studies fully comply with the European Norm – EN 1918-2.

The reviewed work clearly describes the historical reservoir behaviour and mechanism. However, the use of the reviewed simulation model should be limited to material balance calculations. In order to improve the model to allow well planning and qualitative forecasting the performance of the reservoir during injection and production operations significant improvements will have to be made. It is recommended to at least improve the geological description of the reservoir and to improve the grid system of the dynamic model.

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Reservoir engineering work on the Bergermeer gas storage development is on-going.

TAQA informed K&H that improvements and recommendations described in this review have been recognised and are considered in the on-going work.

2 Introduction

This report is structured into 9 chapters.

Chapter 1 gives an short summary of the starting situation, the results and the work done. Chapter 2 contains basic information about the Bergermeer field and a list of the data, that was made available for the study, as well as a illustration of the Project Phases. Chapter 3 enlights the relevant aspects of the European Norm EN 1918-2 for the Bergermeer Project. Chapter 4 describes our review of the work done (geological and dynamic model). Chapter 5 deals with additional questions for the Bergermeer Project (Maximum Storage and Injection Pressure, Seismicity and Subsidence, Sand Production). Chapter 6 presents the results and conclusions of our work. Chapter 7 describes K&H's relevant references.

2.1 Basic field info

The Bergermeer gas field is part of the onshore Bergen concession. The field has been on production since 1971. The original gas in place was estimated as $17.4*10^9$ sm^3. The Bergermeer gas field is separated into two compartments which communicate through a semipermeable fault. The field is nearing the end of its field life and it is considered to convert it into underground gas storage (UGS) facility.

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2.2 Available Data

The following data was provided by Taqa by means of a corresponding FTP server access:

2.2.1 Reports and presentations

- Bergermeer UGS Modelling Study, Phase 1, Part 1-Static Modelling, By Horizon Energy Partners BV, February_June 2008, pp.127.
- Bergermeer/DATA/Data-Phase1/Report/HEP_Bergermeer_report_v10_part1.pdf
- Bergermeer UGS Modelling Study, Phase 1, Part 2-Dynamic Modelling, By Horizon Energy Partners BV, February_June 2008, pp.165.
- Bergermeer/DATA/Data-Phase1/Report/HEP_Bergermeer_report_v10_part2.pdf
- Bergermeer UGS Modelling Study, Phase 2, By Horizon Energy Partners BV, March 2008, pp.146.
- Report on Summer Injection Test
- Presentation on PVT Study
- Bergermeer/DATA/Data-Phase2/Report/HEP_Bergermeer_phase2_rpt_final.pdf
- Bergermeer Seimicity Study, TNO report 2008-U-R0871/B, Utrecht, Sept.2008

2.2.2 Other data

- GWC measurements (plus RFT from Eclipse runs)
- Summary of all History Match (HM) runs

- 34 HM Eclipse models (23 BAG, 7 BGM, 2 GRT, 2 BER)
- Petrel model
- Core data (Petrography, BM 1 core reports, SCAL reports for BGM 1 and 2 and corresponding Excel files)
- GWC measurements for BGM 1 and GRT 6)
- LAS files for BER, BGM, GRT
- Production and Completion data (p/z for BER, BGM, GRT; production history for BER, BGM and GRT; completion depths and properties for BER, BGM, GRT)
- Excel sheets on PVT Data
- Well Test data/interpretation (PAN system files; various tests for each well; sapphire plots)
- High/Medium/Low case in Eclipse for BAG models
- Compositional PVT data (original and 2007 gas composition, reference PVT analysis of Gas Condensate)
- Model files (phase envelopes and compositions; CGR calculations; Prosper EOS files/projects)

3 Assessment of UGS Project according to EN 1918-2

3.1 Status of the EN 1918-2

The EN 1918-2 is the European Standard for gas supply systems - underground gas storage, dealing with functional recommendations for storage in oil and gas fields.

This European Standard was approved by the Comité Européen for Normalisation (CEN) in February 1998. For CEN members this European Standard has the status of a national standard without any alteration. The

Netherlands are CEN members and therefore EN 1918-2 has the status of a national standard.

This standard does not specify ranges and limits but procedures to be followed.

- K&H expertise is restricted to subsurface issues of the Bergermeer gas field.

3.2 General Statements

- The geological formation, in which the Bergermeer UGS is planned, is satisfactorily known and well understood.
- The Bergermeer gas field was operated for a period of 35 years, starting from June 1971 until the end of 2006. This demonstrates that the storage is capable of ensuring long-term containment of the stored gas through its mechanical and hydraulic integrity. There is no doubt in this respect and no further investigations are necessary.
- The Bergermeer gas field has a history of induced seismicity during the production of hydrocarbons. A detailed technical review has been carried out by TNO and is described in reference 4. The geomechanical behaviour will not be discussed in this report.
- The surrounding formations and their relevant characteristics were identified. There is no doubt in this respect and no further investigations are necessary.
- The operation of the UGS will not cause any inadmissible ground movement at the surface. The largest subsidence measured since the start of depletion is 10.5 cm. Predicted maximum uplift during injection is 6 cm, while the maximum subsidence during the following production is estimated to be 2 cm.
- TAQA followed a systematic methodology in field development, data acquisition and investigations.

- Current state of technology was applied in the development and operation of the Bergermeer gas field.
- Proven technologies were used for analysis and calculations.
- Relevant analyses and calculations are documented.
- The technologies applied are proven and common practice in the oil and gas industry.
- The preliminary design of the UGS was carried out by competent personnel and companies.

3.3 Field Description of the Bergermeer Gas Reservoir (EN 1918-2, Chapter 4.2)

- All available data were thoroughly reviewed.
- The trapping mechanism of the Bergermeer field is sufficiently known. Open questions and uncertainties resulting from shortcomings in the data and their interpretation do not change this statement.
- The structure of the reservoir and its closure is sufficiently known. Uncertainties resulting from shortcomings in the data and their interpretation do not change this statement.
- The boundaries of the proposed storage formation are sufficiently delineated.
- The fault pattern in the proposed storage formation is sufficiently known. There is limited uncertainty due to the unknown position of the extension of the main dividing fault between the reservoir blocks as it is not fully seen by the seismic.
- The sealing capacity of surrounding formations and boundary faults is considered as proven based on the pressure history of the field.
- There is no communication between the Bergermeer UGS formation and surrounding formations. There is a negligible risk of subsurface

gas loss across the spill-point to Groet or Bergen. Therefore the question for a spill-point situation or insufficient confinement is obsolete.

- The sedimentology of the reservoir was determined and validated by core evaluation. The Bergermeer reservoir unit is part of the Upper Slochteren Formation, which is characterized by dunes and sandflats facies.
- The reservoir properties (permeability, porosity, capillary properties and saturations) were properly evaluated. Some uncertainty remains in respect of permeability and the reservoir quality in the Bergermeer 7 compartment. Regarding the EN 1918-2, the distribution of all these parameters throughout the reservoir is not a critical point. The uncertainties resulting from shortcomings in the data and their interpretation do not change this statement.
- The initial gas-water-contact (GWC) for the Bergermeer main compartment is exactly known. The movement of the contact was monitored. In the Bergermeer 7 compartment wells were drilled after production and the initial gas-water-contact (GWC) for this compartment was estimated with sufficient accuracy.
- The OGIP is fixed with a relatively high degree of accuracy. Because of the uncertainty in the orientation of the extension of the mid field fault, some uncertainty remains on how the volume is distributed between the Bergermeer main and Bergermeer 7 compartment. The amount of OGIP is $17*10^9$ sm^3. This value was estimated from the volumetrics of the geological model and validated by material balance calculations and history matching of the simulation model.
- The Bergermeer gas field is a closed, volumetric gas reservoir where no water influx occurs and no communication with other reservoirs exists. The drive mechanism is an expansion drive.
- The well capacities were determined from the well test data. During the UGS operation the well capacities rather depend on pressure limitations (maximum injection pressure, minimum wellhead

pressure, surface facilities etc) than on petrophysical properties (productivity index).

- All existing wells are intact.
- Well test information, pressure and production history from the proposed storage and surrounding formations were analyzed to estimate the capacity of the storage reservoir. The reservoir dynamic properties were determined by a material balance calculation and numerical reservoir simulation.
- The physical and chemical properties of the native hydrocarbon are known. The gas is sulfur-free. The composition of the injection gas is not known.

3.4 Determination of the Maximum Operating Pressure (EN 1918-2, Chapter 4.3)

The European Standard EN 1918-2 specifies, that based on the overall description of the caprock, the overburden, the structural situation, the sealing capacities of faults and the technical situation of all wells penetrating the storage formation, the maximum operating pressure for the storage facility shall be determined so that the following risks are avoided:

- Risk of mechanical disturbance
- Risk of gas penetration through the caprock
- Risk of uncontrolled lateral spread of gas

In the Bergermeer field these requirements are assessed as follows:

- The lithology of the caprock is well known from the drilled wells. Additionally the lithology of the caprock is characterized by cores and log measurements.

- Petrophysical and hydraulic characteristics of the caprock are satisfactory known.
- The geometry, structure, thickness and lateral extension of the caprock is mapped.
- Continuity of caprock is through the original gas accumulation proven.
- Fracture gradient was not examined but due to the low operating pressure no such an investigation is required.
- Gas penetration into the caprock by displacement of water out of the caprock does not need special investigation; the seal is guarantied at the low operating pressure.
- All faults were proved sealing to neighboring formations.
- The possibility of gas penetration into the caprock due to technical defects in wells is, based on the current state of the wells, negligible.

The EN 1918-2 recommends the limitation of the maximum operating pressure of the reservoir by the lowest pressure value from:

- The fracture pressure of the caprock.
- The pressure at which the well integrity could be affected.
- The calculated pressure resulting from the water pressure in the caprock plus the threshold capillary pressure of the caprock, if available.

Because TAQA is not intending to increase the reservoir pressure above the original pressure of 228 Bar, these limiting pressures are not applicable.

3.5 Wells (EN 1918-2, Chapter 4.4)

- There is no need for measures and measurements above the usual code of practice.
- The proposed storage wells are concentrated in clusters.
- It is assumed by K&H Oil that the newly drilled storage wells will be cased and equipped according to the planned injection and withdrawal conditions.
- It is assumed by K&H Oil that the UGS wells will be equipped with sub-surface and surface safety valves.
- There are no doubts in terms of integrity of the well systems.
- The composition of the original reservoir gas is not corrosive. The composition of the storage gas is not known.

3.6 Monitoring (EN 1918-2, Chapter 4.5)

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- The movement of the gas-water-contact (GWC) is monitored in wells BGM1 and BGM7.
- The storage behaviour, the extend of the gas phase and any losses are identified and analyzed by simulation studies.

3.7 Neighboring Subsurface Activities (EN 1918-2, Chapter 4.6)

K&H is not informed about any planned subsurface activities in neighboring areas.

3.8 Additional Regulations (EN 1918-2, Chapters 5, 6, 7)

The European Standard EN 1918-2 includes three more chapters dealing with

- The construction of surface and sub-surface facilities (EN 1918-2, Chapter 5).
- Testing and commissioning (EN 1918-2, Chapter 6).
- Operation, monitoring and maintenance (EN 1918, Chapter 7).

These chapters include guidelines routinely applied in the oil and gas industry and will not be discussed in this report.

3.9 Conclusions

The reviewed studies fully comply with the European Norm EN 1918-2.

In the case that operational injection pressures exceed the initial reservoir pressures, additional analysis are required:

- Testing and commissioning (EN 1918-2, Chapter 6).
- Analysis of fresh cap rock cores (capillary threshold pressure and permeability)
- Mapping of cap rock and overburden.

As the cost of those additional analyses is relatively small and offers Taqa the possibility to operate at pressures exceeding the initial reservoir pressure in the future, K&H recommends to have those analyses carried out.

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4 Description of the Bergermeer Gas Field

4.1 Geological Model

4.1.1 Geophysical Evaluation

4.1.1.1 Available Data

One seismic line with interpretation is available in the presentation BERGERMEER-WORKSHOP-2007-06-05-G&INTRODUCTION. This interpretation looks good. The completeness of data provided for the evaluation of the geophysical work has to be checked. The size, parameters of the 3D seismic and seismic processing details are not enclosed in the data.

4.1.1.2 Quality and Uncertainties in the Interpretation

A review of the provided time maps reveals that either the seismic data or their interpretation has some deficiencies. With increasing depth of the layers we can easily spot strong undulation in the time maps. It can be clearly stated that these undulations are with highest certainty artefacts and not related to any geological feature. These undulations clearly influence also the interpretation in the crest of the reservoir and may indicate non-existing faults. During conversations with the responsible geophysicist of TAQA, it was found out, that the undulations were left in on purpose in order to point out data weaknesses and not claiming unsupported accuracy of the seismic interpretation.

4.1.1.3 Time-Depths Conversion

The available data provide little information about the Time-depth conversion performed. A v(z)= V(0)+kz formula is typically used in the southern North Sea. The Rotliegend uncertainty map indicates a maximum error of about 60 to 80 meter. With an average depth of just 1700-1800 m the presented error margin of 4-5 % appears too high.

4.1.1.4 Structural Modelling

As already mentioned strong and easy to spot parallel undulations are visible in the time maps. They influence the geometry of the reservoir and certainly increase the uncertainty of the structural model. Furthermore it can be assumed that faults (as seen as separator between the Groet and the Bergermeer Field) and running parallel to those undulations might be artefacts only and in reality non existing. TAQA has informed K&H that the presence of baffles can be interpreted from actual well tests and from pressure measurements with down hole gauges in various wells during an injection test during the summer of 2007.

4.1.1.5 Reservoir Base and Top

As stated in the time–depth conversion procedure little is known about the parameters and the exact procedure of the time-depths conversion. On top it is assumed that also the crest of the reservoir is affected by the artificial undulations visible in the time maps of the seismic interpretation. In light of these observations the uncertainty is most likely underestimated even with an error margin of 50 meter.

4.1.1.6 Fault Modelling

Given the limited information provided, in absence of any seismic data and the given time, it is difficult to make any statement about the fault modeling. It only can be reiterated that any faults running parallel to the direction of the undulations is most certainly artificial and in K&H's opinion incorrect.

4.1.2 Petrophysical Interpretation

The Petrophysical Study conducted by Horizon Energy Partners (HEP) relies mainly on a previous study conducted by BP ("Petrophysical Evaluation of the Bunter, Zechstein and Rotliegende Formations", 2004). The workflow and the methodologies used in this study seem reasonable considering the quality and quantity of input data. Where necessary HEP conducted their own investigations on available data to investigate key issues and to retrace the workflow by BP.

4.1.2.1 Input Data

The bulk of the studies shortcomings must be attributed to the availability and the quality of the input data. The source of the raw logs, especially for the raw wells, is ambiguous. There is circumstantial evidence that density logs where created synthetically from sonic logs for wells where no density log was run. The lack of a density correction log (DRHO) and unusually good correlation between density and sonic log with almost no scatter in the data, are indications for this.

In addition the logging tool used for some of the older logs is unknown. This poses an additional source of uncertainty especially for applying environmental correction.

From the reports it is evident that both BP in the previous study as well as HEP were aware of these limitations and accordingly used the data with caution.

4.1.2.2 Petrophysical Methodologies

Volume of shale is considered very low in the Bergermeer reservoir formations and was thus evaluated rather qualitatively and combined to a lithology description together with "lithology flags" that would mark e.g. carbonate streaks, salts and anhydrites. The resulting lithological column was then used to guide the determination of matrix properties. K&H

experts would designate this procedure as a simplified facies-based petrophysical interpretation and sees significant potential of improvement in this respect. TAQA informed K&H that the approach was chosen because of the relative low importance with respect to purpose of the dynamic model to represent the historical production behaviour.

Porosity was mainly derived from the density log. The density log is the most reliable of the three porosity logs in clastic reservoir rocks. For some wells however the sonic log was used because the density had very low readings. The sonic log has a very short radius of investigation and is thus considered less reliable. The low density section are predominantly in the Rotliegend and are assumed to be cemented by Anhydrite. As a matter of fact there are other explanations for such log readings such as borehole washouts or gas effects which can not be easily discarded. A more thorough investigation and a proper electrofacies (efacies) study could give more insight into the matter.

According to HEPs report no correction for hydrocarbon effects were done for the porosity. However, they mention a systematic over-prediction of core porosities in well BGM1 and discrepancies in average porosities in wells BGM1 and BGM2 which could be a result of exactly this effect. Other sources of error could be the shale correction.

Water saturation was computed using the Archie equation which is strictly speaking only valid for shale free formations. Due to the rather qualitative character of the shale correction and the assumed rather low clay content this seems adequate. Varying Archie parameters were taken for the geological formations and determined through Pickett plots where no laboratory data was available.

Finally a permeability – porosity relationship was derived from core data. The cross-plots indicate that the correlation of the data seems to be quite good. The permeability modeling is mentioned later in the text.

4.1.2.3 Results and Conclusions

The petrophysical study is generally consistent and complete, there is room for improvement:

An interpretation based on electrofacies might help to resolve issues coming from the heterogeneity of the formations. Especially in the Zechstein which reportedly have quite inhomogeneous composition and features such as radioactive salts which are easily mistaken for shale, or for the low density section of the Rotliegenden mentioned above, a more thorough interpretation could improve the overall quality of the study.

Environmental corrections of the logs as well as accounting for gas effects seems to be necessary for this type of reservoir.

Core – log depth mismatch is mentioned to be likely. This is a shortcoming of the petrophysical study since matrix parameters need to be derived by core versus log data cross-plots and the log porosity must be calibrated to core porosities of the same depth. TAQA informed K&H that this mismatch has been investigated. The available data is insufficient to decide on the order of mismatch. This is especially caused by lack of gamma ray changes and by the fact that a significant part of the cores have fallen apart during coring. Besides that HEP’s conclusion was that any plausible shifts would not alter the porosity-permeability relationship significantly.

4.1.3 Evaluation of the Static Model

4.1.3.1 Regional Structural Geology

The regional structural geology is well understood, some unclear questions were discussed in depth with Taqa and explained in a satisfactory way. In this respect, K&H did not see any open questions and/or critical points.

4.1.3.2 3D Modeling Workflow

4.1.3.2.1. Facies Modeling

The Bergermeer reservoir unit is part of the Upper Slochteren Formation, which is characterized by dunes and sandflats facies. This could be validated by Horizon Energy Partners, who reviewed cores of well BGM 1, BGM 2 and GRT 3. The dominant facies in the cores of BGM 1 and BGM 2 were described as sandflat facies, whereas the core of GRT 3 is dominated by dune deposits.

Open hole logs in the Bergermeer field show that the gamma ray curve is relatively featureless, but porosity logs indicate a subdivision of the Rotliegend into three zones. The lowermost zone has been drilled in wells BGM 1 and BGM 8A and is characterized by a thickness of approximately 40 meters and an average porosity of 15 %. This zone is overlain by a relatively thicker section with average porosity of 25 % and a thickness of approximately 150 meters. The top section is 40 to 50 meters thick and is characterized by average porosities of 15 %. Within all zones, the porosity logs indicate the presence of thin interbeddings with thicknesses of a few meters and comparably lower porosities (around 15 %). These interbeddings are referred to as "low porosity streaks" by Horizon Energy Partners and can be seen in all wells, but cannot be correlated between the wells. According to Horizon Energy Partners, these low porosity streaks could not be related to facies changes observed on cores. This indicates that the type of rock does not differ from the rock in the high porosity zones.

The facies classification in the Bergermeer Field was entirely based on interpreted log porosities, where one facies type comprises the intervals with good porosity (background facies), and the second facies type represents the low porosity streaks. According to the provided report, the facies classification was done by visually classifying intervals on the porosity log as background facies or low porosity streaks.

A facies model was then constructed by using object modeling, a stochastic object modeling technique that is based on the random insertion of facies bodies with predefined geometry into a background facies. For the facies modeling of the Bergermeer Field, the high porosity intervals were designated as background facies, whereas the low porosity bodies were modeled as elliptical facies bodies, whose size was varied from several hundred to several thousands of meters to create three different facies realizations.

K&H appreciates the efforts that have been made to construct a facies model for the Bergermeer Field that captures the true heterogeneity of the field. After a detailed review of the provided report and the Petrel model, the conclusions and recommendations of K&H experts regarding the facies classification and modeling procedures are the following:

1. The applied analyses and methodologies correspond to the best practice in reservoir characterization.

2. The statement that the low porosity streaks cannot be correlated between wells has been validated. In the absence of any correlative patterns, K&H confirms that stochastic facies modeling is a commonly used and accepted practice to investigate different scenarios.

3. The visual classification of porosity logs into good background facies and low porosity streaks is somewhat arbitrary. A similar classification could have been obtained by applying a porosity cut-off, where intervals with porosities lower than the selected cut-off should be classified as low porosity streaks, whereas all other intervals are classified as background facies.

4. Horizon Energy Partners used object modeling to distribute low porosity facies bodies. Object modeling is a modeling algorithm that is commonly used when the size and geometry of facies bodies is well defined, which is typically the case when (1) the presence of particular facies types can be related to certain depositional environments, or (2) well control is dense enough to delineate size and shape of the facies bodies. For the facies modeling of the Bergermeer Field, K&H experts

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recommend using Sequential Indicator Simulation, where the spatial continuity of facies bodies can be analyzed using variogram analysis.

4.1.3.2.2. Petrophysical Property Modeling

Porosity modeling in the Bergermeer Field was conditional on the generated facies models. Porosity was distributed spatially using Sequential Gaussian Simulation; to cover a broad range of possible scenarios, the variogram range was varied between 300 meters and 5000 meters. In addition, porosity models were developed for the different facies models, resulting in a total of five different porosity models constructed for the Bergermeer Field. One of the five realizations was then regarded as the final porosity model. Permeability in the Bergermeer Field was modeled by applying the core-derived porosity-permeability transform to the parameterized model.

The conclusions of K&H experts for the property modeling are the following:

- No variogram analysis has been conducted to quantitatively investigate the spatial continuity of porosity. Instead, variogram ranges were selected arbitrarily between 300 meters and 5000 meters. As appropriate variogram ranges are a critical input for Sequential Gaussian Simulation, K&H experts consider the lack of a geostatistical data analysis as a severe shortcoming. TAQA informed K&H that no variogram analysis was applied since the areal distribution of the wells is not considered sufficient to achieve a representative analysis. It is recognised that this can be improved in the future when data from new wells is available.
- The uncertainty in porosity modeling could be significantly reduced by correlating the responses of open hole logs to a seismic inversion cube. Althought the resolution of inversion cubes may be limited, the formation thickness is great enough to investigate variations in porosity for several subzones of the Bergermeer Field. If a correlation between porosity and acoustic impedance can be established, the

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acoustic impedance cube could be used as a basis for variogram analysis.

- It was not evident from the available information why one particular realization has been selected as the final property model. K&H recommends constructing one facies model and one property model that is based on a proper geostatistical analysis that should be considered as the ”most-likely” realization. This realization should be used as the base case for investigating uncertainty and constructing different realizations. TAQA informed K&H that the various models did not vary in quality regarding the history match. The chosen model was considered to be the most realistic case.

4.1.4 Well Testing

4.1.4.1 Quality of Data

The data quality and completeness cannot be fully assessed at this time point. The data mainly contains Pansystem files and text files with pressures and rates. Some files cannot be read. Headers and descriptions on what the text files contain, which tests they belong to, where, when and how the data was measured, how the data was manipulated etc are very rare or completely missing. For some tests reports only the results are given.

The quality of the pressure measurements themselves can be best assessed visually in the Saphir projects where the input data and the corresponding interpretations can be reviewed.

4.1.4.2 Quality and Uncertainties in Interpretation

The first impression of the interpretation results is ambiguous. TAQA recognises this and informed K&H that the goal of the historical well tests was to determine the well performance at different tubing head pressures (multi rate tests) rather than collection of pressure and rate data for pressure transient analysis.

In some cases, such as the welltest for BGM1-1986 the imported pressure data seems to be very scattered and discontinuous which becomes especially visible in a close up review of the build ups. It seems that interpretations were attempted, however, the value of such modelling results is dubious. The most promising interpretation is given in BGM1-1990. Stabilization in the derivative can be clearly identified which improves the reliability of the derived parameters such as permeability or skin.

The BGM3 well tests are of good quality and the interpretations seem plausible. The well tests and interpretations for wells BGM6 and BGM7 vary in quality.

All in all, the value of the interpretation results of the available welltests should not be overestimated. The quality of the input data and correspondingly the interpretations strongly vary between the tests, in some cases the quality of the measured pressures does not seem to allow a reliable interpretation, in other cases at least a qualitative statement on permeability and skin can be made. The best interpretation output can be used as a qualitative tool to support assumptions and conclusions from other data sources. Better quality checking and manipulating of the input data might improve some results.

4.1.5 Salinity

Unfortunately no formation water analysis data exist. The brine salinity and density were estimated from the resistivity of the Rotliegend. On this basis the brine shall be salt saturated with a reservoir density of 1230 kg/rm^3. The estimated GWC's of the three fields were settled consistent with this density. A light shifting of the GWC's (115 m difference between BGM and GRT instead of 120 m) would already reduce the brine density by 50 kg/sm^3. K&H did not find stronger information in the reports supporting the figures of brine quality.

The exact knowledge of salinity is in two respects crucial:

- The density and the viscosity of the water have a strong impact on the reservoir mechanism. In fact these data have more influence on the dynamic modeling as the relative permeability.
- The dry injected gas is will be saturated with vapor in the reservoir, which could lead to salt precipitation. *Note: this is only a problem when continuous water supply to the "dried out" areas is available and salt can plug pores.*

For the reservoir simulation the water properties were created applying the Petrel RE default correlation. The surface density calculated using this correlation equals 1233 kg/m^3. TAQA informed K&H that during the current winter production from the existing Bergermeer wells water and condensate PVT samples will be taken for compositional analysis.

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4.1.6 Gas Composition

Table 4.1: Gas composition for BGM (left) and GRT (right)

Component	Moles
Nitrogen	0.970
Methane	94.535
Carbon dioxide	0.699
Ethane	3.048
Hydrogen sulfide	0.000
Propane	0.444
I-Butane	0.086
n-Butane	0.079
I-Pentane	0.024
n-Pentane	0.024
Hexanes	0.019
C7+	0.072
Total:	100.000
C7+ Mole Weight	116
C7+ Density, g/cc @ 60F	0.7931
Gas Gravity	0.590
Default C7+ MW	100
Default C7+ Density	0.70

Component	Moles
Nitrogen	2.986
Methane	92.272
Carbon dioxide	1.044
Ethane	2.922
Hydrogen sulfide	0.000
Propane	0.437
I-Butane	0.050
n-Butane	0.085
I-Pentane	0.026
n-Pentane	0.024
Hexanes	0.025
C7+	0.129
Total:	100.000
C7+ Mole Weight	116
C7+ Density, g/cc @ 60F	0.7931
Gas Gravity	0.603
Default C7+ MW	100
Default C7+ Density	0.70

The gas composition is known for Bergermeer and Groet. The composition of the Bergen gas was calculated backwards from existing Z-data, which can not provide acceptable results. The differences between BGM and GRT compositions are large enough to regard them as separate units.

4.1.7 Gas-Water Contacts

In the Bergermeer field most wells do not show an obvious transition zone. The logs indicate a clear contact without a transition zone. There are some differences in the S_w level reached by the different wells, however;

e.g. BGM3, which has the GWC in the (poorer) upper Rotliegend, has higher S_w levels, but does not show a clear S_w gradient.

In well BGM1 the GWC has been monitored. The results of these measurements were available. In addition, wells BGM7 and BGM8 were drilled post-production, and give some information on contact dynamics.

The initial gas-water contact in the well BGM1 is 2227 mTVDSS. A contact rise of 21m was monitored in August 2006. BGM7 was drilled in the year 1980. The observed GWC was 2231 mTVDss at a reservoir pressure of 158.2 bara. The deeper GWC is a result of expansion of the gas trapped in the compartment. It is unlikely that the initial GWC could be different to the BGM main. The pressure history showed that the two compartments communicate not only through the bottom water but also through the interval saturated by gas. This observation offers the possibility to calculate the relative volumes of the compartments and to determine the fault transmissibility. Unfortunately of the GWC in well BGM-7 could not be observed in a later time due to the presence of a fish (tubing tail end).

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4.1.8 Initial Pressure

The initial reservoir pressure was 228 bara at a reference depth of 2100 mTVDss. The reservoir temperature is 86.1°C.

4.1.9 Volumetric Determination of Fluid in Place

The OGIP of the Bergermeer modeling area was calculated using different reservoir structures and reservoir parameter such as NTG (net to gross), porosity calculated for the five different porosity modelling scenarios, S_g (gas saturation) and B_g (bulk gas) leading to a range of $12*10^9$ to $21*10^9$ sm^3. This range can be misleading. Based on earlier investigations and recent MB and numerical simulation calculations the OGIP is $17.4*10^9$ sm^3 with not more than +/- 3% uncertainty. Therefore only these static model realizations, which satisfied this constraint, should be presented and should be used for dynamic modeling.

Based on the geological concept the Bergermeer field shall be a closed volumetric gas reservoir where no water influx occurs and no communication with other reservoirs exists. This statement needs naturally a confirmation from side of dynamic behaviour. Nevertheless it would be advantageous to calculate the OWIP volumetrically and to determine the range of uncertainty.

Table 4.2: Bergermeer volumetrics

Bergermeer100 midcase

Scenario	BGM main [*10^6 sm3]	BGM_7 [*10^6 sm3]
discontinous	14182	1988
mid-low	14470	1843
mid-mid	14313	1849
mid-high	14371	1771
continous	14954	1938

Bergermeer100_LowCase

Scenario	BGM main [*10^6 sm3]	BGM_7 [*10^6 sm3]
discontinous	9890	1349
mid-low	10146	1377
mid-mid	10165	1253
mid-high	10209	1185
continous	10544	1087

Bergermeer100_HighCase

Scenario	BGM main [*10^6 sm3]	BGM_7 [*10^6 sm3]
discontinous	18095	3079
mid-low	18429	3106
mid-mid	18353	3011
mid-high	18845	2968
continous	18990	2888

4.1.10 Spill Point

Bergermeer and Groet are two separate reservoirs with different GWC's and gas composition. From the point of view of the static (geological) model they could communicate through the bottom water layers. In such a case it would be necessary to define a spill-point, i.e. the closure depth. Based on the structural interpretation this could be at the depth of 2240 mTVDss or deeper. The initial GWC was at 2227 mTVDss and raised to 2207 mTVDss in 2006. Also from this reason it is unnecessary to consider any danger of spill.

4.1.11 Aquifer

From geological point of view the reservoir is not connected to any larger water bearing formation. Water inflow could be assumed from the North edge only, where no sealing fault(s) were identified. The existence of Groet field and the lack of pressure interference between Groet and Bergermeer exclude this possibility also. The absence of an outside connected aquifer is proven by dynamic calculations as it will be shown later. Therefore Bergermeer is without any doubt a closed volumetric gas reservoir.

4.2 Dynamic Modeling

4.2.1 Material Balance

4.2.1.1 p/Z Analysis

HEP provided p/Z plots for all of the three reservoirs. All of them show clearly that they are volumetric gas pools without communication and without aquifer influence. HEP discussed possible reasons for moderate deflections from the straight lines. These discussions overstrain the method itself and can suggest false conclusions. Still, according to recent publications, there is the possibility for some water to come into the reservoir although the p/Z plot exhibits a straight line behaviour. The deviations are caused by the difficulty to determine the exact average reservoir pressures by the limited inter-compartment communications and the considerable water amount in the reservoir. The water expands contemporary with the gas and causes contact rises.

Although HEP studied the possible presence of an aquifer to explain the contact rise, K&H does not see any discrepancy between “the contact rise on the one hand, and lack of evidence in the pressure data for any aquifer on the other”. K&H strongly states that it does not see even a “little evidence of any communication between the fields”.

4.2.1.2 Multi-Tank Material Balance Calculation

HEP used the MBAL® software package. The constructed model consists of 4 tanks, GRT, BER and two BGM compartments. Potential aquifers were added to all tanks and transmissibilities were specified between the tanks. This model set up implies that the four units potentially communicate through the gas zones but no communication is assumed via a common aquifer. Such a model contradicts all observations and investigations so far. It is evident that the two BGM compartments are connected, probably in both in the gas bubble and in the bottom water. A connection between BGM and GRT or BER is physically possible through the aquifer only. Caused by discrepancy between model and reality the MB calculations do not offer any supplementary awareness.

The GRT and BER p/Z plots showed already that no outside energy sources exist or if than it must be so small that the method will not be able to identify them. Therefore the MB calculation should be done standalone for both reservoirs. The result will be the same as from p/Z plot and the magnitude of the aquifer constant will be in the range of the numerical errors.

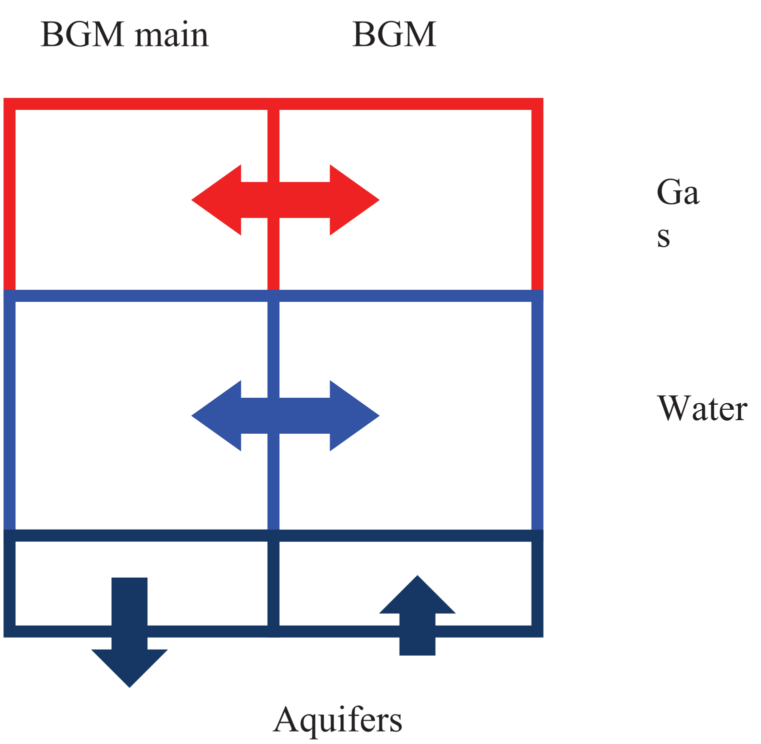

Figure 4.1: K&H suggestion for Bergermeer material balance model

Figure 4.1 shows a possible relevant model setup for BGM material balance calculation. Both compartments have their own production, pressure and phase contact histories. It is assumed that only gas is flowing between the two units. At a given model set up (i.e. fluids in place for both compartment) the water efflux will be calculated for both compartments. One of them will be positive (inflow) the other negative (outflow). Under the assumption that all water is beside the tanks and expands contemporary with the gas, the sum of this should be zero over the whole history. This requirement allows determination of the best fitting figures for the fluids in place, the gas and water overflows as function of time.

To verify this assumption K&H made some preliminary MB calculation using its proprietary software package. All input data (production and pressure history, PVT, vertical distribution of pore volumes, etc.) were taken from the HEP base case ECLIPSE model.

Based also on these results K&H concludes that both the volumetric as the mechanism of BGM is well understood and accurately described.

4.2.2 Simulation Model

The grid model was constructed for the whole area of interest, including BGM, GRT and BER. Nevertheless no runs were done with the BER field in connection with other fields. The combined BGM and GRT model supported all previous investigations that showd that there is no reason to assume any connections in the past or in the future between the two pools. K&H believes that neither the accuracy of the input data nor the applied simulation tool makes it possible to verify a possible connection in the assumed small magnitude or to predict any future consequences. From this reason K&H restricted his review to the stand alone reservoir simulation work of the Bergermeer field.

The dynamic behaviour of the Bergermeer gas field was numerically simulated using a 58x182x10 grid, resulting in 11800 active grid blocks. K&H considers the grid resolution as sufficiently high and appropriate for numerical reservoir simulation. The employed software tool for numerical reservoir simulation was Eclipse 100.

Eclipse 100 is the standard software tool for numerical reservoir simulation in the oil and gas industry. Nevertheless Eclipse offers many none state-of-art and questionable features which are applicable with carefulness and under certain conditions only. It is the responsibility of the consultant not to use them if the feature could result in wrong answers.

K&H made simulation runs based on the BGM_ALT2 data set to gain deeper insight in the HEP's work and to better understand the reports. These runs are not documented and also not considered in the conclusions. The following discussion is based on the reports [2] and [3].

A numerical reservoir model can be constructed on many levels, with more or less demand in respect of geological and petrophysical verity, physical correctness and numerical accuracy. The best model is the simplest one which can give the right answer on the actual questions. In this respect two questions arise:

- Does the model verify the geological concept of the field and explains and describes the reservoir mechanism? Is the model suitable to assess uncertainties in these respects? Does the model testify the applicability the reservoir as underground gas storage by assessing possible risks.

  K&H believes that the answer is YES.

- Is the current simulation model(s) already a suitable/optimal tool to plan future developments, to optimize well placement and configuration (slanted, horizontal or multilateral wells), predict phase movements during the UGS cycles?

  K&H is believes that that the answer is NO

The following sections contain positive and critical notes. The critical ones are related to the second question and do not alter the first one.

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4.2.2.1 Bergermeer Grid Model

The static reservoir models, constructed with Petrel®, were used directly as simulation grid. The only difference is the vertical layering: the 150 static model layer was upscaled to 25 and to 10 simulation layer. The 10 layer simulation model was used for history matching.

This kind of gridding can be false from the flow simulation point of view. Petrel uses non-orthogonal pillars based corner point geometry which is up from less suitable to wrong for flow calculation. Using two point flux approximation the grid must be orthogonal (or k-orthogonal with tensorial permeability) and the grid lines must be vertical. Together with a non-orthogonal grid multipoint flux approximation must be used. It is believed that the corner point geometry more precisely captures geological objects as faults and baffles than an orthogonal grid, therefore a certain degree of compromise in both direction could be a practical solution. Petrel offers an aid for the user giving information how strongly the grid is distorted. This possibility of control was not used.

The dynamic behaviour of the Bergermeer gas field was numerically simulated using a 100x100 m grid block size and a 58x182x10 grid, resulting in 11800 active grid blocks. Figure 4.2 - Figure 4.4 show the areal distorted and vertically displaced grid blocks at some locations and cross sections. The horizontal and vertical scales are identical, so the optical distorting is the real one. Eclipse 100 does not have an option for multipoint flux approximation therefore the simulation model is not suitable to model local flow behaviour as vertical movement of phase contacts or communication through a fault. Appendix 1 compares cases with vertical and with displaced grid lines, showing how large the error in saturation distribution can be in a case of skewing the grid.

In case of Bergermeer the grid displacement in Figure 4.5 and Figure 4.6 and at many other places is considerable. Consequently this grid model is applicable to model global behaviour (offering advantages compared to a material balance) but is not optimal to investigate well placement, well configuration (slanted, horizontal or multilateral wells) or vertical phase movements.

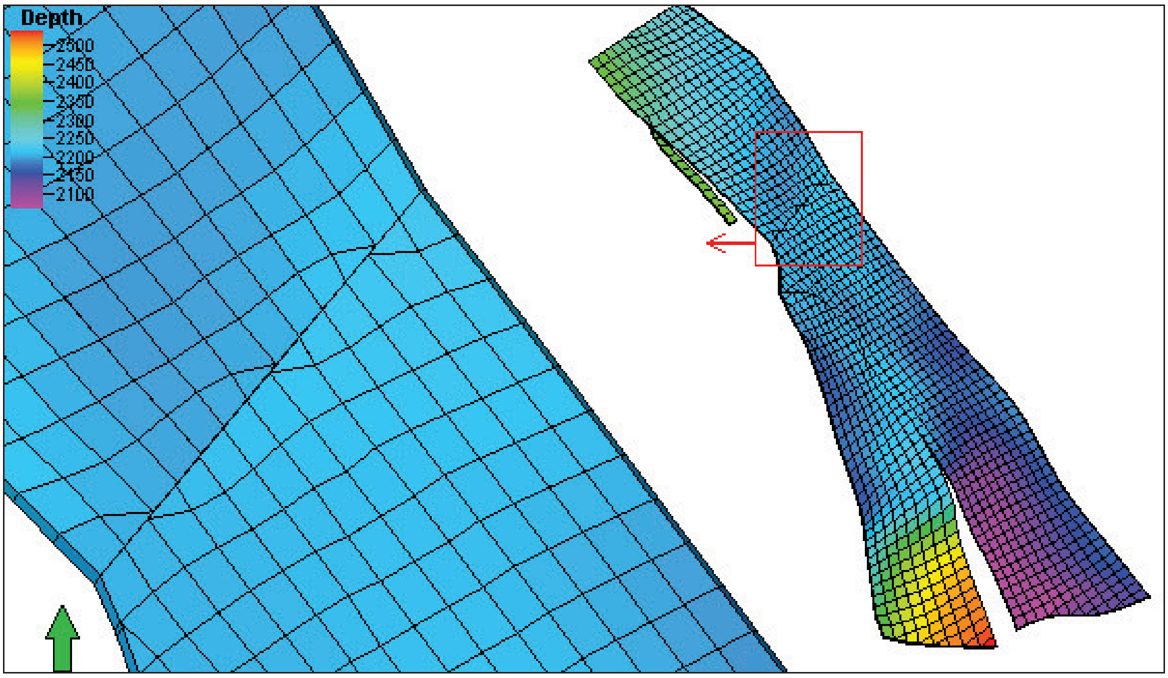

Figure 4.2: Areal view in K = 1 showing depth distribution and distorted grid in vicinity of Fault 7

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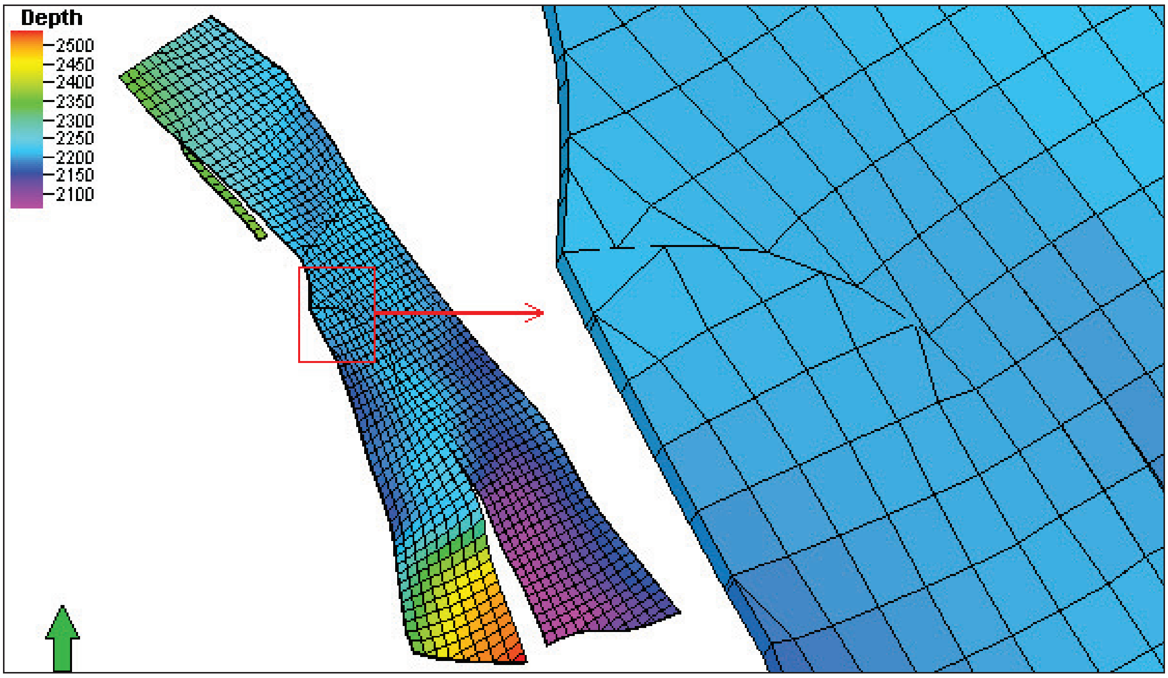

Figure 4.3: Areal view in K = 1 showing depth distribution and distorted grid in vicinity of Fault 2b

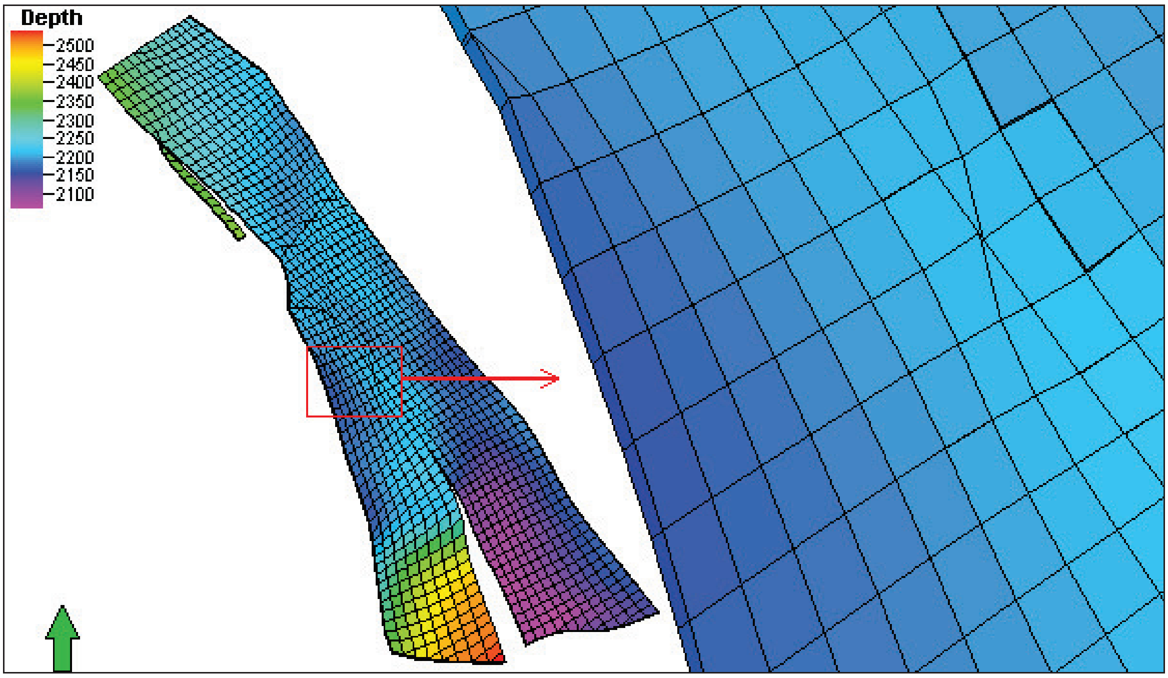

Figure 4.4: Areal view in K = 1 showing depth distribution and distorted grid

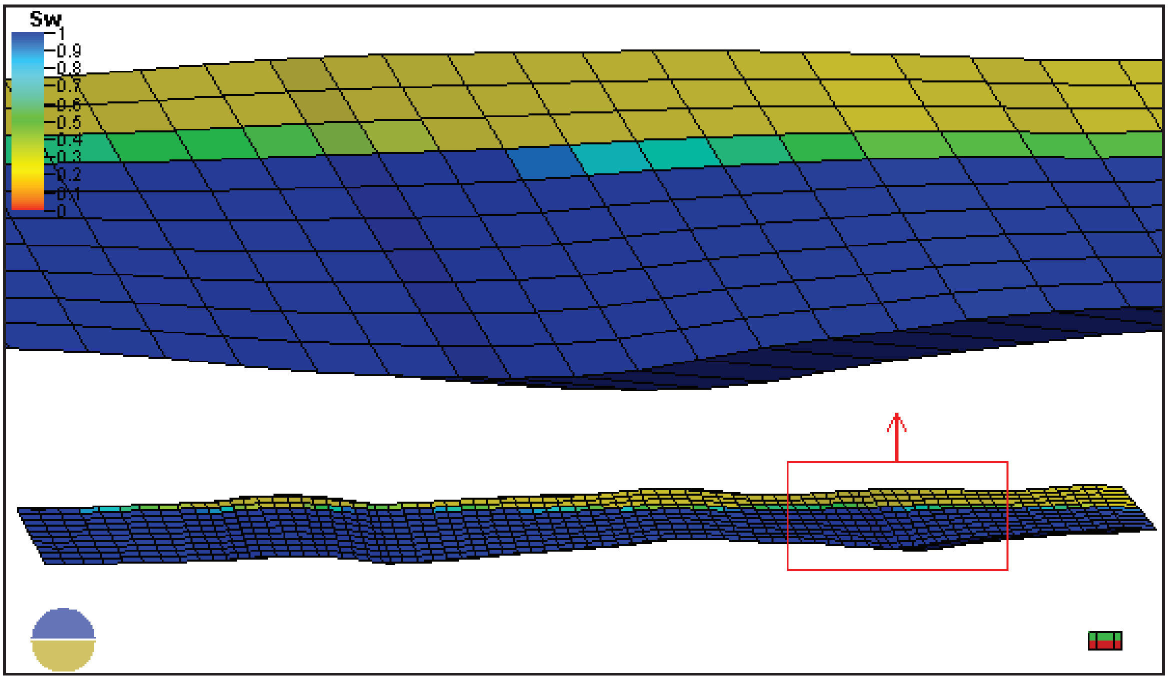

Figure 4.5: Cross section in I = 46 showing initial water saturation

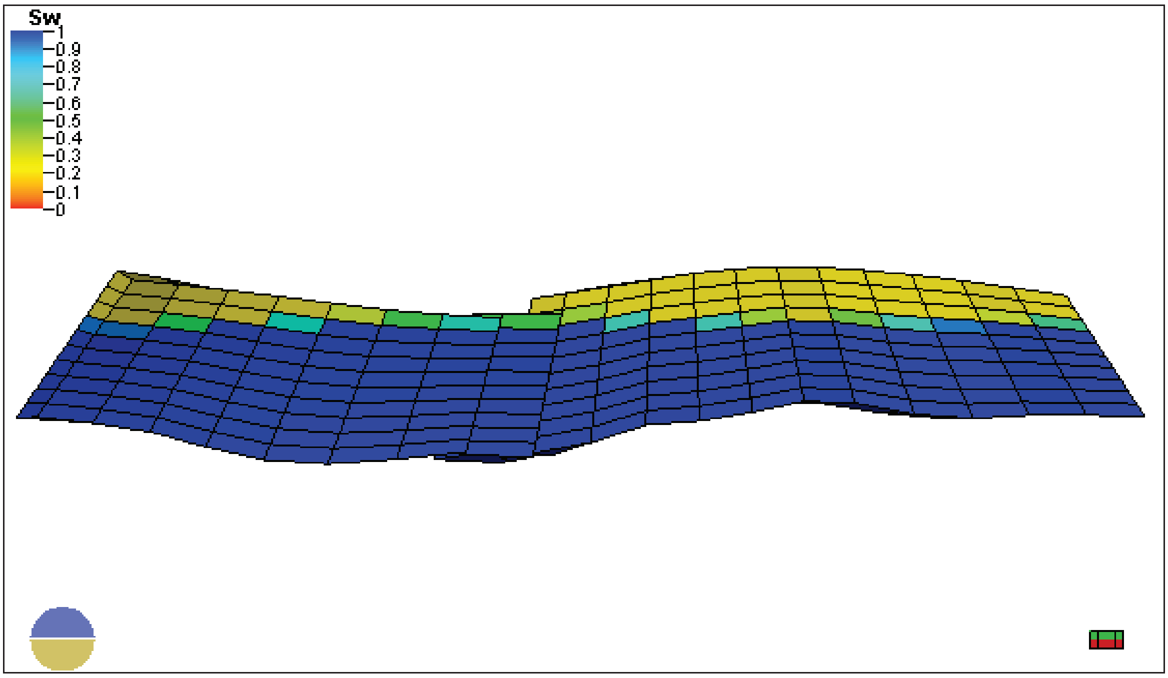

Figure 4.6: Cross section in J = 147 showing initial water saturation and slanted pillars

4.2.2.2 Grid Properties

One structural model realization was used for reservoir simulation. This structural realization is referred to as “Bergermeer100_midcase”. Based on an uncertainty map for the top Rotliegend two additional different realizations of top horizons were created. They are referred to as “Bergermeer100_LowCase” and “Bergermeer100_HighCase”. The two latter ones were not used in reservoir simulation. The base case structural realization “Bergermeer100_midcase” is lower than the real structure.

Regarding the grid properties the model ‘DISMID_HIGHKV’ (or ‘DISCONT_MID_HIGHKV’) is the most likely model for Bergermeer, as found in sensitivity analysis by HEP. This model has the least extensive low-porosity streaks. Also the average horizontal permeability is somewhat lower than in the other models, but it has substantially higher vertical permeabilities. The model parameters as used for the UGS are summarized below in Table 4.3.

The following upscaling algorithms were used in the upscaling of properties on the simulation grid from the static model grid:

- Porosity: Arithmetic
- Permeability: 'Tensor'
- Facies (where used): 'Most Of''

4.2.2.3 Other Input Data

4.2.2.3.1. PVT and SCAL Data

The gas composition and a Hall-Yarborough based computation of gas properties were available. A detailed PVT report was not available. The reservoir fluid properties were modeled using a dry gas model. Gas condensate production was not modeled as no information on dew point or condensate production were available. Further no formation water analysis was available. The water properties were taken from the Petrel RE default correlation.

The special core analysis reports of wells BGM1 and BGM2 were used as input. The capillary measurements from the SCAL reports were not used in the Bergermeer simulation model because the logs indicate a clear contact without a transition zone. As the irreducible water saturation is fixed by the logs this value was preferred over the SCAL data by HEP. In the simulation model one rock region was used.

4.2.2.3.2. Production and Pressure History

The production history was available. There is no information about water production. For the time period 1972-1976 only field allocated production data are available. The allocated historical production volumes per individual well were applied. The K&H experts believe that this approach is appropriate.

Static pressure surveys are available for the Bergermeer main wells from 1971 to 2006 and for Bergermeer-7 from 1980 t o1997. Build up and/or gradient data on which the measurements are based were sparsely available. The data were not quality checked.

4.2.2.3.3. Contact Movement

The movement of the gas-water-contact was monitored in well BGM1. Wells BGM7 and BGM8 were drilled post production and give some information on contact dynamics. As some contact measurements were performed after high rate production periods it is not clear if the water level was given enough time to settle. The last measurement done in August 2006 confirms a contact rise of 21m in well BGM1. The initial gas-water-contact for Bergermeer was at 2227 mTVDSS.

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TAQA informed K&H that additional GWC measurements were recently carried out in wells BGM-1 on 18-7-2008 and 27-10-2008. According to Taqa. the simulated dynamic behaviour of the GWC is consistent with the actual field measurements.

To match the gas-water-contact movement in the model RFT data were regularly extracted from the Eclipse runs and gradient intersections were used to ascertain that the contact movement is caught in the history match. K&H believes that this could have also been accomplished by surveying the water saturation in the simulation model regularly.

TAQA informed K&H that the method of extracting simulated RFT data was chosen because of the grid block sizing and relatively small changes in GWC.

4.2.2.3.4. Well Test and Completion Data

The well test data were analyzed in terms of well performance. Quality checks were not performed. At a later stage more detailed analyses were performed and the permeability of simulation model was adjusted. This was described in the report of Phase-2.

TAQA informed K&H during a meeting that in the ongoing work a match between actual well tests and simulated well tests was achieved.

The completion history files were used as input for the reservoir simulation model. The information includes perforations, reperforations, squeezes and stimulations. For the simulation the skin was assumed to be zero.

4.2.2.3.5. Other Data

For the simulation no other data were available, especially no RFT, PLT and rock mechanical data.

4.2.3 History Match

The history match (HM) was successfully conducted with Eclipse 100. Seven equally probable realizations of the history matched Bergermeer model were made. The models are history matched on pressure behaviour and gas-water-contact rise. The calculated OGIP in the history match ranges between 17.1 and 17.8 sm³, which corresponds to the result of the p/Z plot. The history match was achieved without employing an analytical aquifer model.

The reservoir is a closed volumetric gas reservoir i.e. the aquifer impact is negligible and rock, shale and water compressibility's are negligible compared to the compressibility of the gas. In the reservoir no water influx occurs and no communication with other reservoirs exists.

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4.2.3.1 Model Description

The static modeling offers a series of geological realizations from which only those are acceptable for history matching which satisfy the OGIP constraint. The OGIP with $17.4*10^9$ sm^3 +/- 3% is univocal testified by the production history and the material balance calculation. Choosing one of these models with no porosity multiplier would be necessary. Anyway the porosity and connate water saturation from cores and well logs are satisfactorily known and there is no reason to change them. The main uncertainty is the reservoir top as was already worked out by HEP. This topic is currently worked out in more detail related to well planning by TAQA.

In fact HEP used in Phase 1 History Match a single realization in both structural and property respect. This is the 'DISMID_HIGHKV' (or'DISCONT_MID_HIGHKV') model and should be, according to HEP, the most likely model for Bergermeer. This model has the least extensive low-porosity streaks. Also the average horizontal permeability is somewhat lower than in the other models, but it has substantially higher vertical permeabilities. The model parameters as used for the UGS are summarized below in Table 4.3. It should be noted that the properties are *overall* averages for the model. A pore volume multiplicator of 1.14 (+14%) was used on the Bergermeer geological model. The authors characterize their approach as "practical". K&H believes that it is only correct to use a global pore-volume multiplier when the dynamic model is used for material balance calculations. When the model is to be used as a well planning tool, this porevolume multiplier has to be reduced.

TAQA informed K&H during a meeting that this issue is currently being resolved.

Table 4.3: Reservoir properties DISMID_HIGHKV model

Porosity [%]	Permeability (Kh) [mD]	Kv / Kh	Avg. width low-perm. streaks [m]
19.7	601	0.502	250

Figure 4.7 gives an overview of the seven history matched models. The models differ in:

- Fault settings: BGM_ALT1 and BGM_ALT2 scenarios
- Aquifer: BGM_ALT1_AQU and BGM_ALT2_AQU scenario
- Rock compressibility (BGM_ALT2_CR2),
- Residual gas saturation (BGM_ALT2_RLP1)
- Corey coefficients ((BGM_ALT2_RLP2).

The production history of the Bergermeer field indicates that the reservoir is split into two compartments, the Bergermeer main compartment and the Bergermeer-7 compartment. The two compartments are separated by a fault. Some uncertainty is adhered to this fault as it was derived from the pressure behaviour of the two compartments and cannot be fully tracked on the seismic. For this reason two fault scenarios with different northward extensions of the main dividing fault were created for the history match.

The BGM_ALT2 realization is defined as the base case history match, in which the fault separating the Bergermeer main compartment and the Bergermeer-7 compartment is bent northeastwards. In the BGM_ALT1 realization this separating fault is bent northwestwards. The best fit with dynamic data was obtained with the northeastwards bending fault i.e. BGM_ALT2 fault scenario.

The base history match includes:

- A pore volume multiplier in order to fix OGIP.
- A fixed fault transmissibility of the main fault that separates the Bergermeer main and Bergermeer 7 compartment.

- The contact rise in the Bergermeer main compartment is matched by permeability multipliers.
- No local changes of properties or faults were done in the history match.

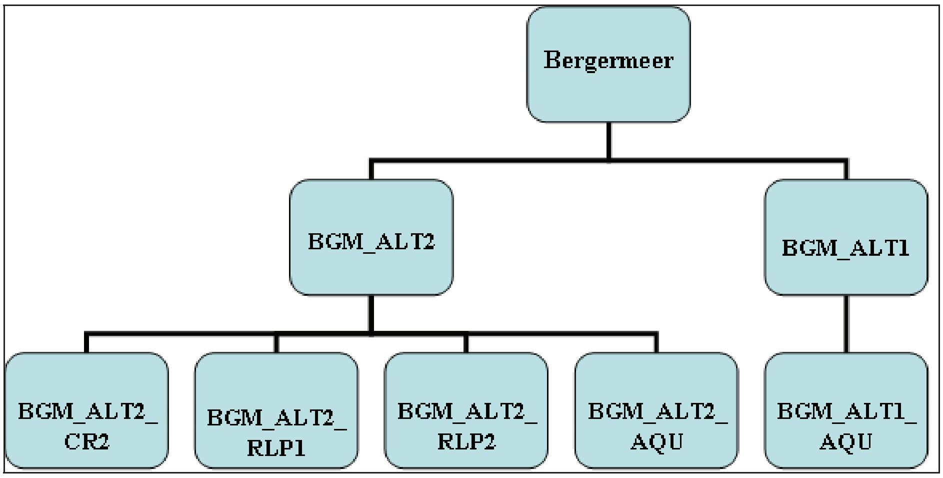

Figure 4.7: Bergermeer HM realizations

The application of a pore volume multiplier was required to obtain the correct OGIP. Possible and likely suspects for the cause of this problem are

- Structural issues: uncertainty regarding the top surface of the reservoir (time-depth conversion) as discussed above
- Parameterization of the simulation model: The sensitivity analysis on various model realizations shows that pore volume multipliers below 1 and above 1 were used. In case of a correct parameterization the OGIP is also correct. It is not insignificant where in the model the pore volume is missing as this affects the distribution of fluids in the reservoir model also. Still the uncertainty observed in pore volume is, from the point of view of static modeling, in an acceptable range.

The fault transmissibility multiplier for the main dividing fault is 0.0002. Additionally a transmissibility multiplier of 2 is applied in x- and y-direction.

The net-to-gross ratio is 1 over in the simulation model.

The additionally investigated realizations examined the influence of higher rock compressibility (BGM_ALT2_CR2), higher residual gas saturation (BGM_ALT2_RLP1) and application of different Corey coefficients ((BGM_ALT2_RLP2).

Further for both, BGM_ALT1 and BGM_ALT2, a setup employing an analytical aquifer model was investigated. A Fetkovich type aquifer was connected to an extended water leg of the Bergermeer 7 compartment in the south of the field. The initial water volume of the aquifer was set to $2*10^9$ m³ and the productivity index to 3 (m³/day)/bar. It has to be noted that the Bergermeer field could be history matched assuming no aquifer and no connectivity to other fields. Nevertheless a weak aquifer connected to the Bergermeer 7 is possible. This could be verified by measurement of the contact movement.

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The result of the HM seemingly did not give a solid basis for prediction of the future UGS performance therefore alternate models were generated from the DISMID_HIGHHKV model by application of “adhoc” permeability multiplier in the 2nd Phase of HEP study. The multiplier is lower on the top and higher in the middle. The factor has, vertically plotted, a BELL shape profile. The goals were

- to achieve a better accordance between the well test and simulation result
- to have a pessimistic alternate subsurface model i.e. a model with the lowest permeability which allowed a successful HM.

The interpretation of K&H is that none of these goals were achieved. Most of realization showed water break trough and sometimes excessive water production. HEP characterizes one case (BEL_033 run) as “reasonable pessimistic case" but this "has a mismatch on both water and GWC and still contradict the well test results".

4.2.4 Summer Injection Test

In order to improve understanding of historical reservoir dynamics and predict its behaviour during storage operation, an injection test was designed. In specific the purpose was to

- determine the volume distribution between the BGM main and BGM7 blocks
- survey the gas-water-contact movement
- evaluate the pressure behaviour of BGM7 to identify fault transmissibility between the BGM main and BGM7 blocks
- determine the reservoir permeability / porosity-compressibility between injection and observation wells
- calibrate the dynamic reservoir model with pressure behaviour seen during test.

The history matched models (DISMID_HIGHHKV, BEL_033, BEL_055) could reproduce the Summer Injection Test (SIT) to a limited extend. The trends in pressure behaviour as measured in the field could qualitatively be reproduced. The exact pressures, however, were not matched. The positive aspect is that the test did not show discrepancy regarding the gas-water-contact movement. In all other respect the simulation model(s) could not be confirmed. In cases of such a short event is always possible to achieve a "match" by introducing artefacts as faults, baffles, channels etc., but this is not they way to improve the predictive capability of the model. HEP introduced sub-seismic non-sealing fault between BGM6 and BGM3 and also BGM1 and BGM5 without any indication from the geological side. According to TAQA there are indications for a fault between BGM3 and BGM6 on the seismic maps, which indicate a structural dip, and also the

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reservoir tops in the logs indicate a throw between the two wells. Regarding the fault between BGM1 and BGM5, TAQA found indications during the interpretation of interference tests that a non-sealing baffle exists between the two wells.

K&H believes that the necessity of such a structural and property changes can be originated from the incorrect gridding addressed earlier already. As result the difference in pressure between the main compartment (represented by BGM1) and Block II with BGM7 has increased, while not changing the volume distribution. While the average pressure in the main block has decreased with less than 1 bar compared to the previous HM, the BHP difference is greater for the individual wells. BGM3 shows a maximum pressure-increase of 6 bar in 1990 in the new history match.

The summer injection test supports the conclusion of K&H that the predictive capability of the current reservoir model is limited showing qualitative behaviour.

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4.2.5 Well Performance Modeling

HEP used the well modelling software Prosper, version 10.0 (or IPM version 6.0).

The inflow performance of BGM1 (1979 test data) was revisited in order to better calibrate non-Darcy effects around the wellbore in the simulation model. The other main objective was to examine the relative importance of skin in the reservoir vs. friction in the tubing at the high rates to be used in the UGS phase.

PROSPER uses the Forchheimer inflow equation

$$P_r^2 - P_{wf}^2 = AQ + BQ^2$$

which is valid for turbulent flow also. Using the Multi-Rate Jones method the coefficients A and B and also the reservoir pressure can be determined directly from the well test data. This inflow model is theoretically correct and can be used over a wide range of flow rates. In contrary to this the Darcy inflow equation is valid for laminar flow only. The usual extension with a rate depended skin factor is a rough approximation only. This can not be used for wells producing and injecting millions of sm^3/d. Advantage of the Forchheimer equation is that it can be easily combined with the pressure drop calculation in tubing and in flow line, as it is clearly written in the HEP report of phase 2 in section 5.6, p.90-97.

In the Eclipse model, the non-Darcy pressure drop is implemented via the flow dependent skin factor D. The D-factor can be specified as a constant per wells or it can be calculated internal using the Dake formula, which uses a correlation that incorporates porosity, permeability, well radius and perforation length. The Dake type skin factor is calculated for each perforation (i.e. grid block connection) in the well and the total well skin is obtained by summation over the perforations:

$$S_t = S + \mathrm{sum}(Dq)_i$$

The two well performance calculations in PROSPER and Eclipse can not be compared. Statement from HEP: “To compare the well performance sensitivities, the low, mid and high gas-rates were looked up at a reservoir pressure of 120 bar and THP of 80 bar. It should be noted that the PROPSER base case permeability for vertical well inflow of 200 mD is not conform the dynamic model, it should be ca 600 mD”.

It is strongly proposed to improve the ability of the Eclipse model to match the inflow performance, with focus in matching the historical well tests.

TAQA informed K&H that recently a detailed re-interpretation of the well tests has been carried out by an independent party. The result of this review shows that the permeabilities from the well tests have been calculated in the part using to much thickness of the contributing zones. The result is that the permeability calculated from the kh is currently in line with the permeability used in the reservoir model. Also, as mentioned earlier, during on going work the simulation model was matched with the historical well tests

4.2.6 Forecasting

4.2.6.1 Well Planning

The study does not present any quantitative investigation about the number of necessary wells, about the suitable (optimal) well structures and their locations. In lack of an integrated tool HEP uses a heuristic approach to well planning:

"The placement of development wells in Bergermeer is governed by reservoir productivity on the one side and the distance to the GWC on the other side".

"The XL case needed 24 wells in total".

"The horizontal wells are distributed between the less productive parts of the MAIN-block and the BGM7 compartment."

"The vertical wells are perforated from the top Rotliegend to a depth of ca 2180 m TVDss. "

"The horizontal wells are distributed between the less productive parts of the MAIN-block and the BGM7 compartment."

"The horizontal well-length is approximately 500 m, and they are planned at a depth that was optimized between the distance to the original GWC and the productivity in the reservoir."

[Text deleted because of confidentiality]

4.2.6.2 Field Performance

[Text deleted because of confidentiality]

K&H believes that introducing some changes in the current model would aid in enhancing the quality of the forecast considerably. K&H suggests improving the geological model, the history match, decoupling of the reservoir and well modeling and the well configuration and placement. TAQA is currently working on this.

A reliable integrated simulation tool and an equitable matched and verified reservoir-well-surface model would be necessary. The simulation tool should be able to handle transient reservoir conditions, near well flow including turbulence strongly coupled with tubing and flow line.

4.2.7 HEP Summary and Recommendations

HEP summarize its findings as follows:

- High permeable reservoir which is suitable for gas storage
- Not supported by an aquifer
- No or very little water production is expected
- Tilting of GWC explained by presence of best reservoir (‘sweet spot’) in south with most producers / injectors
- The GWC-rise will be reversed by gas injection
- Water breakthrough risk is greatest in the northern area of the field
- The field has two main compartments divided by partially sealing fault
- The Main block is further compartmentalised by at least two smaller subseismic, non-sealing faults
- Horizontal wells are needed in block-II (BGM7) and in the deeper regions of block I (Main)
- The Base Case model has 20 wells with 7 5/8” tubings, producing and injecting gas at ca 3.2 MMsm3/d each

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- The pressure losses in the tubing are much greater than the pressure loss near the wellbore at the designed production and injection rates of the UGS
- Pressure losses in the tubing can be greatly reduced by lowering the tubing-roughness
- The sealing potential of the northern boundary fault to Groet is not known at larger pressure differences than 35 bar.

K&H sees the underlined items above as attested. The other items belong to the category "possibly".

The key uncertainties and related recommendations according to HEP, regarding the subsurface modeling are given in the following list. K&H fully agrees with this. HEP recommendations for supplementary investigations (SI) to reduce the uncertainties and risk were not revised by K&H but they certainly provide a basis for further discussions.

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Uncertainty	Recommendation
Relative volumes Main / BGM7 (position of dividing fault)	Continued pressure monitoring in BGM (on either side of the BGM7/Main fault) during repressurization.
Top Rotliegend in the BGM7 block is uncertain	Drill well in the south of block-2 / new 3D
Reservoir quality and top Rotliegend in the north of the field, due to lack of well control.	Well northeast of BGM3A / new 3D

Sealing potential of the fault between Bergermeer / Groet at higher differential pressures.	Continuous monitoring of pressures in GRT1
Possible discrepancy between well test and history match permeabilities.	Simulation of the well tests done in Eclipse (i.s.o. a PTA package like Kappa) to accurately assess the effect of heterogeneities.Running of PLT's during future tests to better define contributing reservoir section height, which is essential to calculate k from k*h.
Un-known non-Darcy skins of new wells	Assess impact of openhole gravelpack / slotted liner on non-Darcy D-value versus perforated casing/liner

The key uncertainties for well planning with recommended potential mitigating measures are:

Uncertainty	Recommendation
Steel quality of tubing	Investigate UGS standard
Mechanical well-skin due to drilling and completion in low pressured reservoirs	Investigate analogues / gravelpack specialist

Amount of re-vapourised water / condensate during production cycle	Quality of the injection gas

The main achievement of the HEP studies is that all critical questions were clearly worked out. It was also demonstrated which methods are insufficient to handle Bergermeer UGS and in which way a more accurate planning and performance prediction would be possible.

5 Attendant Questions

5.1 Maximum Storage and Injection Pressure

The European Standard EN 1918-2 specifies, that based on the overall description of the caprock, the overburden, the structural situation, the sealing capacities of faults and the technical situation of all wells penetrating the storage formation, the maximum operating pressure for the storage facility shall be determined so that the following risks are avoided:

- Risk of mechanical disturbance
- Risk of gas penetration through the caprock
- Risk of uncontrolled lateral spread of gas

The EN 1918-2 recommends the limitation of the maximum operating pressure of the reservoir by the lowest pressure value from:

- The fracture pressure of the caprock.
- The pressure at which the well integrity could be affected.
- The calculated pressure resulting from the water pressure in the caprock plus the threshold capillary pressure of the caprock, if available.

5.1.1 Caprock

Detailed investigation regarding the existence and the continuity of a gastight caprock is necessary only if is anticipated that the maximum operating pressure could be exceeded. In Bergermeer this is not the case. The initial pressure is 238 bara and the maximum injection pressure is planned to be 150 bar.

Independently from this the caprock and the overburden should be adequately characterized in the following respects:

- The lithology;
- The petrophysical and hydraulic characteristics;
- The geometry with respect to structure, thickness and lateral extension;
- Geological discontinuities or other features which may affect the containment above original reservoir pressure;
- Fracture gradients.

None of these aspects were discussed in the TAQA reports [1]-[4] available to K&H. K&H assumes that these questions would or will be sufficiently investigated and documented.

5.1.2 Fracture Gradient

The documents submitted to K&H by TAQA do not contain any information in this respect. On the basis of the correlation published by OGCI this should be at or above 0.2 bar/m. Since the planned injection pressure is deep below the initial reservoir pressure there is no reason to investigate this question.

5.2 Seismicity and Subsidence

TAQA has contracted TNO Built Environment and Geosciences to investigate the seismic hazard and subsidence associated with Bergermeer UGS independently. TNO BE&G is an international recognized organization in this field. The work was carried out on the highest possible level using state-of-art methods and software tools.

K&H does not see any reason to question the finding, conclusions and recommendations of TNO BE&G.

5.3 Sand Production

No sand problems were mentioned in the studies available [1]-[4]. It is mentioned that the new wells will be completed with gravel pack, which means that there exist concerns of possible sand production.

During depletion the production rates did not exceed 1 $MMsm^3/d$. Under UGS conditions the rates can exceed 3 MMsm3/d at relatively low pressures (~100 bar) which creates a different situation.

From reservoir engineering point of view a possible sand production is not a serious problem because it can be overcome by an appropriate completion of the wells. A sand intrusion could reduce the productivity, could lead to borehole collapse and as final consequence a loss of the well. The question of sand mobilization and borehole stability should be investigated. A corresponding statement with appropriate documentation is required by the Norm EN 1918-2.

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6 Conclusions and Suggestions

6.1 Conclusions

- All in all, according to K&H Oil's audit, the Bergermeer UGS study is a solid integrated study.
- The reviewed studies fully comply with the European Norm EN 1918-2.
- Based on earlier investigations and recent MB and numerical simulation calculations the OGIP is $17.4*10^9$ sm^3 with not more than +/- 3% uncertainty.
- The material balance and numerical simulation models verify the geological concept of the field, explain and describe the reservoir mechanism. These models testify the applicability of the reservoir as underground gas storage and in parallel assess possible uncertainties, too.
- The reservoir is a closed volumetric gas reservoir. This conclusion is based on a sound geological concept, indubitable confirmed by dynamic behaviour of the reservoir. No water influx into the reservoir occurs and no communication with other reservoirs exists. Also from this reason it is unnecessary to consider a spill point or any danger of spill (see Section 4.1.10).
- The predicting capability of the existing simulation model(s) is limited. The models are currently not suitable to optimize well placement and configuration (slanted, horizontal or multilateral wells), nor to predict phase movements during the UGS cycles (see Chapter 4.2.6).
- TAQA informed K&H that some of the main recommendations given in the corresponding chapters of this audit are already being worked out.

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6.2 Suggestions of K&H for Further Investigations and Studies

K&H report contains greater number of hints for possible improvement. This section summarizes the most important ones.

- K&H recommends constructing a new facies and a new property model that are based on proper geostatistical analysis. That should be considered as the"most-likely" realization. This realization should be used as the base case for investigating uncertainty and constructing different realizations.
- Beside the OGIP also the OWIP should be determined for both Bergermeer compartments volumetrically and should be confirmed by appropriate material balance calculations.
- Future static reservoir model constructions should be strictly constrained by the well known fluids in place (OGIP and OWIP). Other models are senseless and could lead to wrong dynamic models and false development scenarios, only.
- The key suggestion of K&H is to elaborate a simulation model, that is a suitable tool to plan future developments, to optimize well placements/configurations and that can predict phase movements during the UGS cycles. Such a model will be necessary for the daily UGS operation too, determining what gas volumes can be delivered until when.
- The simulation grid model should be orthogonal with vertical grid lines. K&H does not recommend the usage of a non-orthogonal pillar based corner point geometry for flow simulation. Suitable gridding software packages with link to Eclipse are offered on the market.
- TAQA used the software Prosper for well inflow modelling. Prosper is based on the theoretical correct quadratic Forchheimer equation instead of Dupuit equation with turbulence skin factor as available in Eclipse. K&H suggests using quadratic equations not only for inflow calculation but also for the well bore and flow-line modelling.

- A reliable integrated simulation tool and an equitable matched and verified reservoir-well-surface model would be necessary. The simulation tool should be able to handle transient reservoir conditions, near well flow including turbulence, strongly coupled with tubing and flow line.
- During the drilling campaign sufficient cores should be gained from overburden and cap rock. Representative samples should be investigated for capillary threshold pressure and permeability. Such measurements can be done on fresh cores only. This data should be available if TAQA will consider higher operating pressures. Also the cap rock should be mapped (topdepth and thickness).

7 References

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