Guidance on calculating blowout rates and duration for use in environmental risk analyses

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PREFACE

This guidance on calculating blowout rates and duration for use in environmental risk analyses is an updated version in English of the Norwegian Oil and Gas Association´s Norwegian report entitled *Retningslinjer for beregning av utblåsningsrater og -varighet til bruk ved analyse av miljørisiko*. The original report was first published in 2004 and revised in 2007. It was prepared by Thomas Nilsen in Statoil with support from colleagues Nina E B Jacobsen, Arne Myhrvold, Espen Fyhn Nilsen (all Statoil) and Tone Roald (Hydro). Minor revisions and corrections have been made to this English edition by Thomas Nilsen.

Before starting to translate and update the report in 2014, two Norwegian Oil and Gas expert networks were invited to comment on the original (Network on Environmental Risk and the Drilling Managers Forum). Relevant consultants (Add Wellflow, Acona, DNV GL and Akvaplan-niva) were also invited to comment on the 2007 report. Rolf E Gooderham has carried out the translation in close cooperation with Thomas Nilsen (Statoil).

Norwegian Oil and Gas also engaged Add Wellflow to prepare a new document with guidance for blowout rate simulations – data basis and scenario selection*.* This is intended to serve as a supplement to the existing guidance on the treatment of uncertainty related to blowout rates and duration in environmental risk analyses. It will provide a guideline for those involved in data collection and/or simulation of blowout rates for use in environmental risk analyses. The supplement offers an overview of data requirements and how the parameters can affect the results for various flow scenarios. The same networks and consultants were again invited to comment on this text.

This last revision (2021) includes minor adjustments and references made necessary by the publication of the new amendment to this guideline titled “Recommendations on blowout scenario modelling for environmental risk analysis of exploration wells” and is prepared by Thomas Nilsen (Equinor).

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1 SUMMARY

Calculating the flow rate and duration which might be encountered in the event of a blowout forms part of the management of environmental risk when planning well activities by the petroleum industry on the Norwegian continental shelf (NCS). The operator companies conduct environmental risk analyses in order to predict and quantify possible damage to environmental resources as a result of future drilling, completion, operation and maintenance activities. Assessing risk associated with possible blowouts of oil and condensate is a major issue in such analyses. The calculated risk is compared with criteria for acceptable risk, and subsequently incorporated in the basis for dimensioning oil spill response.

Various methods are used across and within the operator companies when calculating blowout rates and durations. Moreover, great variations exist in the level of detail in the analyses, the way uncertainty is dealt with, the conceptual framework used, and the degree of documentation and traceability.

This document aims to contribute to standardising the conceptual framework, methodology and documentation when calculating blowout volumes and thereby to simplify communication of analysis results and to strengthen confidence in these among decision-makers.

The preconditions for this type of assessment vary substantially across drilling and well activities on the NCS. Examples of such variations include differing well designs, downhole conditions during various types of operations, geological factors, operational conditions, the degree of uncertainty in operating parameters and the exposure and sensitivity of the environmental resources affected by oil spills. When developing this guidance, emphasis has therefore been given to the need for flexibility in selecting calculation procedures.

A reference methodology, describing various factors which must be taken into account in the rate and duration calculations, overall analysis principles and documentation requirements, forms the starting point for the guidance. This methodology provides a very detailed procedure compared with current analysis practice. Analyses to this level of detail will primarily be relevant in connection with operations which are very challenging in environmental terms. For most other applications, the risk level, the degree of uncertainty or the decision-making context will permit one or more elements in the reference methodology to be simplified. In many cases, substantial simplifications of the analysis could be appropriate. The purpose of the reference methodology is to establish a common base line for assessing what are to be regarded as simplifications in a given analysis. The guidance specifies requirements for making such simplifications in practice and are directed in part at handling uncertainty and documentation requirements.

Neutral or not particularly conservative calculations require fairly detailed analyses. The main principle in this guidance is that, when simplifications are introduced in models and descriptions of uncertainty, they must act in a conservative direction and the assessments which the simplifications are based on must be documented.

In 2021 an amendment to this guideline was issued titled “Recommendations on blowout scenario modelling for environmental risk analysis of exploration wells" with the aim to contribute to standardisation industry with regards to some of the modelling choices made in analysis of blowout rates and duration for exploration well environmental risk analyses.

Abbreviations, notations and symbols

Alarp	As low as reasonably practicable
BOP	Blowout preventer
CT	Coiled tubing, a type of work string used in well interventions – known as coiled tubing operations
E	Expected value, E(X), is the mean value of the probability density function of the uncertain quantity X
f	Probability density, f(x), is the probability density function of the uncertain quantity X
HPHT	High pressure/high temperature reservoirs or wells
NCS	Norwegian continental shelf
NEA	Norwegian Environment Agency
P	Probability, P(A), is the probability (a single number between 0 and 1) that incident A will occur
PSA	Petroleum Safety Authority Norway
Q	Flow or blowout rate, measured, for example, in cubic metres per day, tonnes per day or kilograms per second
ROP	Rate of penetration, drilling speed
TLV	Threshold limit value
WL	Wireline, a type of work string used in well interventions – known as wireline operations
WO	Workover (heavy well maintenance or modification)

Definitions

Alarp

Risk reduction principle. Measures which reduce risk are implemented if the risk-reduction effect is not significantly disproportionate to the cost of implementation.

Area of influence

Area where drift calculations indicate that the probability of being affected by an acute oil spill is five per cent or higher.

Blowout
Uncontrolled flow of formation fluids from a sub-surface reservoir to the external environment.

Blowout duration
Time, T, from the start of a blowout until it has ceased.

Blowout rate
The volume of formation fluids which flow during a blowout to the external environment at the outflow point per unit of time, Q. Can be expressed as a function of time $Q(t)$.

Blowout scenario
A blowout scenario in a well is given by the type of operation, the reservoir concerned, the kind of equipment found downhole and its depth and condition, other possible mechanical restrictions in the well, and the flow path.

Bottom-hole pressure
Pressure at the bottom of the well.

Conservative value
A value which deviates from the expectancy value in the direction regarded as unfavourable in the given context.

Distribution
See probability.

Expected value
Average of possible outcomes, weighted by their respective probabilities.

Flow path
The channel along which the formation fluids flow from the reservoir to the release point during a blowout.

Habitat
A delimited area where a number of species interact – a beach, for example.

Maximum (max) value
The highest possible outcome of an uncertain future quantity, in practice often represented by a high percentile, such as 90, 95 or 99.

Minimum (min) value
The lowest possible outcome of an uncertain future quantity, in practice often represented by a low percentile, such as 10, five or one.

Model
Simplified representation of reality. Used in analyses to capture the most significant factors related to the phenomenon under investigation and the relationship between them in order to achieve a sufficiently good result from an acceptable effort.

Oil spill trajectory simulations
Analysis of the way oil discharged from a blowout will be spread by wind and currents.

Population
Group of individuals belonging to a single species, which is reproductively isolated within a specific geographical area.

Probability
A measure of uncertainty related to quantities which describe the outcome of future activities. Uncertainty related to whether a possible future event will occur is expressed by a single probability figure between 0 and 1. Uncertainty over the future value of a quantity is expressed by a probability distribution, such as $P(Q \leq q) = F(q)$, where Q is the blowout rate. Distributions can also be expressed as the probability density f, which is the first derivative of the distribution F. An example is $f(q)$. This document applies the term *distribution* to both probability distribution and probability density. *See also Uncertainty*.

Probability density. *See probability.*

Probability distribution. *See probability.*

Release point
The point, depth or location where the medium in an uncontrolled blowout leaves the well or the sub-surface and flows into the air or the sea.

Relief well
Well drilled to intersect with a well suffering from a blowout in order to halt the outflow. Heavy mud and possibly cement are pumped down at high speed in order to kill the well. In some cases, more than one relief well may be required.

Resource
Used here to mean *population* or *habitat*, which see.

Restitution time
The time from damage being caused to a resource until it has been restored to its pre-damage state.

Risk
The threat that undesirable incidents which may occur during the execution of a future activity represent. Described as the possible consequences of such incidents and the associated probabilities. Probability distributions for flow rates and duration describe certain aspects of the risk which a future blowout represents for the environment. See also *Uncertainty*.

Scope of damage
The scope of environmental damage, measured by such quantities as the number of individuals killed in a *population* or *habitat*.

Uncertainty
This document applies the concept of uncertainty to the value of future quantities which cannot be predicted with certainty – pore pressure, for example, or whether a well will collapse during a blowout. Uncertainty means that complete knowledge is not available about the quantities and is expressed as probabilities. See also *probability.* The uncertainty concept is not applied to the value of probabilities since these are in themselves an expression of uncertainty.

Well killing
Activities in a well intended to limit and halt a blowout.

Well section
Part of a well between the setting depths for two different casings or liners, or possibly the open part of a well below the last casing section to be set.

Well pressure
Pressure in the well at a given depth at a given stage in an operation (mud pressure or annular pressure are other terms used). The sum of hydrostatic pressure, frictional pressure drop when circulating well fluid, and surge/swab pressure resulting from running the drill string or casing into or out of the well.

2 INTRODUCTION

The threat of environmental damage resulting from a possible blowout represents a substantial component in the environmental risk related to petroleum operations on the NCS. Efforts to limit this risk have a high priority among operator companies, government authorities and interest organisations. Part of the work involves quantifying the environmental risk, which is done by the oil companies – often with the help of consultants. The results of these analyses are used a decision basis by the operators and the government. This document deals with calculating the quantities of oil or condensate released by blowouts. Attention is concentrated on flow rates from and the duration of a blowout, which represent important quantities in environmental risk analyses.

Various approaches to such calculations are taken by the oil companies. The method also varies within companies. The reason for choosing a particular approach is seldom specified, and traceability can be poor in parts of the calculations. Moreover, the interpretation of key concepts used in such calculations is unclear. This means that comparing calculated rates from different fields and companies is not straightforward. It may be unclear which variants of an approach give the best predictions, whether uncertainty has been handled in a consistent way, and how far using a variation of the method is acceptable in a given context.

This document aims to contribute to standardising the conceptual framework, methodology and documentation for calculating blowout volumes and thereby to simplify the communication of analysis results and to strengthen confidence in these among decision-makers.

Calculating quantities discharged from blowouts is a demanding process. Refined calculations call for knowledge of drilling and well equipment in addition to well activities, and involve the application of various physical models used in simulation tools. The analyst must also take account of substantial uncertainty related to a number of key quantities and conditions.

In practice, analyses need to be simplified as much as possible without undermining their value as a decision basis. How far this is possible varies from application to application. Scope could be available for very simplified calculations where activities have a small blowout potential (low rates, for example) or are being pursued in areas with a small potential for environmental damage (far out to sea, for example). Where the potential harm from activities is higher, more extensive analyses could be needed.

The need for flexibility forms the basis for the approach taken in this document. The starting point for the guidance is the description of a reference methodology for calculating blowout rates and duration. The intention with this methodology is to form a common baseline for assessing what must be regarded as simplifications in a given analysis. It represents in itself an extensive procedure, and making full use of the methodology will only be necessary in a few cases. The actual guidance describes the principles for departing from the reference methodology in order to simplify the various steps in a calculation. These principles particularly address the handling of uncertainty and documentation requirements. The reference methodology and possible simplifications of it are further illustrated by the examples provided in Appendix D.

The guidance covers blowouts resulting from offshore well activities, with the release point at or above the seabed. Its area of application is the analysis of the quantities of medium released in terms of flow rates and duration once a blowout has occurred. Analysis of blowout probability is not addressed. Since attention is directed at the potential consequences of a blowout for the environment, only oil and condensate blowouts are considered. However, the principles are transferrable to blowouts involving other media, such as gas, in order to analyse harm to people and the installation.

Conditions further along the cause-consequence chain, such as dispersion on the sea surface or in the water column, drift, or dissolution, are not covered in the guidance.

The guidance does not provide final descriptions of how rate and duration calculations should be performed, with the reproduction of detailed models, formulae or recommended values. Attention is concentrated on overall analytical principles, factors which should be taken into account, practical adjustments and requirements for documentation. Note however, that the amendment to this guideline "Recommendations on blowout scenario modelling for environmental risk analysis of exploration wells" /1/ provides some specific modelling recommendations for exploration drilling.

The rest of this document is structured as follows.

Chapter 3	The role of rate and duration calculations in environmental risk analysis and basic considerations for the guidance
Chapter 4	Presentation of the reference methodology for calculating blowout rates and durations
Chapter 5	Guidance for practical calculations, presented on the basis of the reference methodology
Appendix A	General introduction to the loss of well control in drilling and well activities
Appendix B	Combating and stopping an oil blowout – general description of some methods and mechanisms
Appendix C	Overview of earlier work in this field by Norwegian Oil and Gas or by others. Summaries of important provisions in current regulations and of current practice for rate and duration calculations among operator companies on the NCS
Appendix D	Examples of how the guidelines can be applied in rate and duration analyses.
Supplementary report	Guidance on data collection for and/or simulation of blowout rates to be used in environmental risk analyses.
Amendment (separate document) /1/	Recommendations on blowout scenario modelling for environmental risk analysis of exploration wells

3 APPROACH AND MAIN PRINCIPLES

3.1 Calculating blowout rate and duration as part of an environmental risk analysis

The calculations of blowout rate and duration which are the subject of this guidance form part of an environmental risk assessment for an activity which involves drilling and/or well operations. Such analyses have the following areas of application.

1. Acceptance of a planned individual operation, such as:
   - wildcat and appraisal drilling.
2. Acceptance of a planned installation, such as:
   - a new facility
   - modification of an existing facility
   - changing the level of activity on an existing facility, such as more interventions, workovers and/or drilling operations.
3. Acceptance of a planned activity which requires evaluations at field level, such as:
   - a new field
   - a new facility
   - a substantial expansion of the activity plan.
4. Dimensioning of oil spill preparedness.

Items 1-3 represent the principal application, and concern decisions taken internally in an operator company. Results from items 1-3 are applied collectively in item 4.

To determine whether an activity is acceptable, operator companies evaluate the associated environmental risk against their own acceptance criteria for this risk. Companies operating on the NCS usually relate these criteria to the restitution time for the various environmental resources in the event of acute pollution. The main principle applied for such criteria is as follows.

> The restitution time required after environmental damage must be insignificant in relation to the expected period of time between incidents of such harm.

An example of a detailed criterion which builds on this principle is:

Acceptance if: $P(T_i > 1 \text{ year}) \leq 10^{-3}$

where T_i is the restitution time for a given incident of environmental harm to resource i. The threshold limit value of one year applied in this case is determined by an assessment of the expected return period for the relevant scope of damage and the expected restitution time for the resource. The restitution time is calculated on the basis of the extent of the harm to a given population and of that population’s reproductive ability. The calculated scope of damage builds on an assessment of the quantity of oil in a geographical area, which is based in turn on oil spill trajectory calculations. These incorporate flow rate and duration at a release point.

In a given blowout scenario, all these quantities are in principle uncertain, and the uncertainty[1] propagates through the cause-consequence chain as shown in figure 3.1.

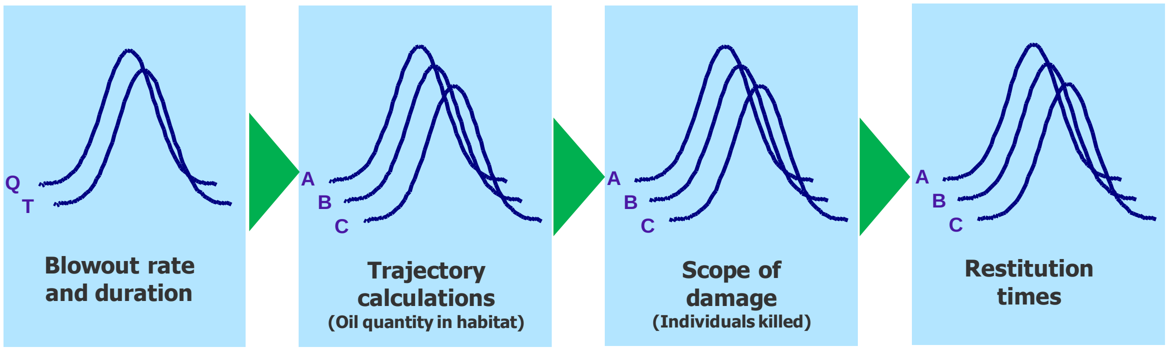

Figure 3.1 Propagation of uncertainty through the cause-consequence chain from the discharge of a volume of oil from a blowout to the restitution time for various resources in the area influenced. The example here shows three resources – A, B and C. (Generalised – normal distributions are equal for the sake of simplicity.)

Acceptance criteria can also be formulated in relation of quantities located further back along the cause-consequence chain than restitution time, such as the scope of damage, the quantity of beached oil per kilometre of shoreline or the quantity of oil on the sea.

In other words, the purpose of calculating blowout rates and durations is to lay the basis for assessing environmental risk – measured, for example, in restitution times for affected stocks and habitats – given that a blowout occurs (illustrated by the uncertainty distributions in figure 3.1). That lays the final basis for assessing whether the probability of these rates/durations will exceed an applicable threshold limit value is acceptable in terms of the company's criteria.

In order to achieve consistent evaluation of environmental risk – expressed as uncertain restitution times – in relation to acceptance criteria, the following is required from the analysis.

1. The results must describe the uncertainty related to restitution times.
2. The results must emerge from individual and overall assessments of uncertainty in each of the sub-calculations:
    - blowout rate and duration
    - oil spill trajectory
    - scope of damage
    - restitution time.

Item 2 means that uncertainty related to blowout rate and duration must be specifically assessed and be expressed as probability distributions. That allows these contributory factors to be accumulated with the other contributions to uncertainty through calculations of oil spill trajectory, scope of damage and restitution time.

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[1] For the meaning of the terms *risk* and *uncertainty*, see the list of definitions on pages 4-5.

Attention in this document is concentrated on the specific uncertainty assessment to determine distributions for blowout rate and duration. If it is desirable to express rate and duration as single figures, such as their expected value or a given percentile, the full distribution should first be calculated in order to determine these.

3.2 Framework for calculating blowout rate and duration

When an environmental risk analysis is conducted, blowout rates and durations are uncertain quantities. The degree of uncertainty and which factors make the biggest contribution varies between the different types of drilling and well activities. An expression for uncertainty related to rates and durations can be provided with probability distributions, conditional on a blowout occurring. These can be used as the starting point for determining simpler expressions for uncertainty, such as the expected value – which would be a neutral prediction – or a more conservative forecast such as the 90th percentile. References in this document to rates and durations mean the probabilistic calculations which lead to distributions for these factors. Other terms can also be used for these calculations, such as quantitative risk analysis (QRA), risk analysis alone, risk assessment, or uncertainty analyses or assessments.

The quality of a risk analysis depends on the one hand on the amount of information or knowledge underpinning it. The overall strength of the information providing the basis for and used in the analysis should be communicated as part of its results.

Account must also be taken of the decision process which the assessment is intended to support. The guidance in this document builds on the following basic analysis principles, which ought to be applied if the results are to carry weight as decision support and documentation.

1. The analysis must build on an assessment of all the factors influencing blowout rate and duration.
2. All assessments must be well- and operation-specific – in other words, the background information used must be relevant to the actual context.
3. All assessments must be documented and traceable.

One of the goals of this type of analysis is to measure the risk against an acceptable threshold limit. That yields the following additional principle.

4. Simplifications in the analysis must lie on the conservative side. Such simplifications yield a higher calculated level of risk than a more detailed and neutral approach.

The level of detail required to provide an adequate basis for deciding whether the environmental risk associated with drilling and well activities is acceptable will vary from case to case. In practice, analyses will always be conducted in such a way that the goal is reached with the simplest possible means. Two main applications can be distinguished, which require differing approaches to the analysis.

1. Operations with a low level of risk in relation to the acceptance criteria – in other words, favourable with regard to one or more of:
    - blowout probability
    - blowout rate
    - blowout duration
    - oil type
    - distance to environmental resources
    - sensitivity of the environmental resources to oil spills.
2. Operations with a high level of risk – in other words, risk in the same or a greater order of magnitude than one or more of the acceptance criteria. These operations will be unfavourable with regard to one or more of the conditions listed under item 1 above.

Where operations involve a low level of risk, compliance with the acceptance criteria could be documented even if substantial simplifications are used in a conservative direction. For operations with a high level of risk, on the other hand, such simplifications could in themselves produce a calculated level of risk which exceeds the acceptance criteria and calls for more refined calculations. How results from a refined analysis and from a more simplified one might differ is shown in figure 3.2.

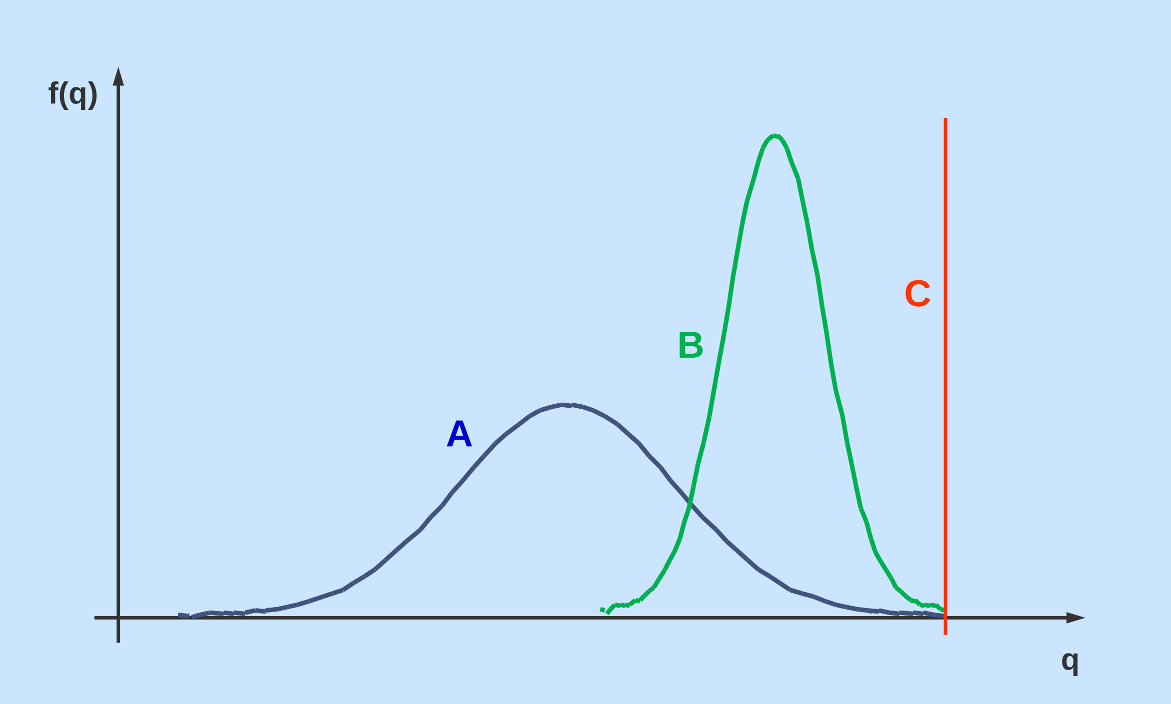

Figure 3.2 Results from analyses of the same operation with different levels of detail – an example with blowout rates: A = detailed analysis, B = less detailed analysis with conservative simplification and C = greatly simplified, conservative analysis. (Generalised – normal distributions used for the sake of simplicity.)

All three of the approaches presented in the figure are adequate for comparison with the acceptance criterion relating to restitution time. The critical consideration in this context is the possibility that outcomes in the right-hand tail of distribution A are incorporated in the subsequent stages of the environmental risk analysis. If the information contained in results A, B and C is fully utilised through the further stages, A will provide a lower restitution time than B, which will in turn be lower than C. In borderline cases, A could lead to acceptance, for example, but not B or C. Should an analysis in such a case not be based on method A to begin with, one procedure could be as follows.

1. The analysis is carried out first with method C.
2. If the calculated risk is higher than the acceptance criterion, the analysis is upgraded with method B.
3. If the calculated risk remains too high, the analysis is upgraded with method A.
4. An acceptable level of risk is documented.

Attention has so far concentrated on documentation of a level of risk in relation to an acceptance criterion. But other reasons could exist for using more detailed analysis methods than being able to document a lower level of risk. The health and safety regulations /2/ issued jointly by the Petroleum Safety Authority Norway (PSA), the Norwegian Environment Agency (NEA), and the Norwegian Directorate of Health emphasise that risk analyses must be used actively to reduce risk in line with the Alarp (as low as reasonably practicable) principle. Risk-reduction measures in an Alarp process will be assessed as part of or in consultation with the technical planning of an operation.

Research points to requirements for this type of risk analysis, which ensures decision support when seeking to reduce risk. See /6/ and /7/, for example. Analyses must:

1. quantify risk on the basis of all relevant information
2. identify critical factors and principal contributors
3. reflect risk-reduction measures.

As discussed in these references, that calls for a certain level of detail in the analyses. In practice, as discussed above, the operations which require detailed analyses in order to demonstrate an acceptable level of risk will largely correspond with those where utilising the analyses in a risk-reduction process is of most interest. A substantial potential for synergies is accordingly presented by closer interaction between analyses of well/operation planning and environmental risk management respectively.

3.3 Principles for the guidance

Because of the need for flexibility over the level of detail in analyses of blowout rate and duration, this guidance does not provide detailed instructions on the way such analyses are to be conducted[2]. Instead, attention concentrates on communicating the principles on which such analyses should build as well as requirements for supporting and documenting analytic solutions and results.

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[2] Some detailed recommendations are provided for exploration wells in the guideline amendment/1/

Chapter 4 presents a reference methodology for the analyses. An analysis conducted in accordance with this methodology will be very refined and detailed. The results can be compared with result A in figure 3.2. It will reflect the uncertainty over rates and durations in a blowout which remains when all relevant information available to a company has been incorporated in the calculations, including experience data, expert judgement, well-specific details, physical models, operational considerations and advanced methods for probability calculation.
However, this reference methodology does not provide a final model or algorithm which can be applied directly to the calculations. Its aim is to identify:

- geological, technical and operational conditions, and the uncertainty related to these, which should ideally be reflected
- principles for the way uncertainty can be identified and handled in the calculations
- what can be regarded as relevant background information
- how the results can be presented
- documentation requirements.

An analysis carried out in accordance with this reference methodology will be resource-intensive, and applying it fully will only be relevant in specific cases where the risk is high in relation to the acceptance criteria, and where a good basis for risk reduction is sought.

In most cases, however, the risk lies at a medium or lower level and efforts will be made to simplify the analysis. The reference methodology is also important in these cases. Its purpose then is to provide a starting point for discussions about which simplifications can be made at various stages in practical analyses as well as requirements for argumentation and documentation related to these.

The actual guidance is presented in chapter 5 and directed at such simplifications. The main message is that simplifications must push the results in a conservative direction.

Appendix D provides specific examples to illustrate the content of the guidance.

4 REFERENCE METHODOLOGY

The presentation of the reference methodology in this chapter addresses the following aspects of rate and duration calculations:

- definition of blowout scenarios (section 4.1)
- presentation of uncertainty related to the course of a blowout (section 4.2)
- blowout rate (section 4.3)
- blowout duration (section 4.4)
- handling uncertainty in the calculations (section 4.5)

Documentation requirements are incorporated in the description of these topics.

4.1 Definition of blowout scenarios

Models used for calculating rates and durations require the analyst to make a number of assumptions about the well system from the reservoir to the release point. A set of *blowout scenarios* must therefore be defined for the operation under consideration.

Blowout scenarios for drilling operations are largely defined through assumptions related to the following.

1. The diameter of the last casing set, and of the hole section which exposes the reservoir.
2. The length of the open hole section (where the reservoir is exposed) when the blowout occurs.
3. The proportion of the open hole section which exposes the reservoir.
4. The flow path and release point.
5. The status of possible restrictions limiting flow in the well, such as:
    - the drill or work string – dimensions and depth position when the blowout occurs
    - possible uncemented casing
    - possible plugs in multilateral or sidetrack drilling
    - partially closed valves at the wellhead or the hole dimension if the release point is elsewhere.
6. The status of the well control systems, equipment and organisation.

Other well activities take place when the well has been drilled and all casing set. These include:

- completion
- intervention
    - wireline (WL) or cable
    - coiled tubing (CT)
    - snubbing (jointed pipe)
    - pumping operations
- well workover (WO)
- normal operation (production or injection).

Where such operations are concerned, items 1-3 specified for drilling operations above will be given in most cases. The following possible restrictions should be considered in addition to those cited for drilling:

- completion type
  - sand screens
  - gravel packing
  - intelligent completions
  - others
- production tubing
- partially damaged packers, depending on flow path
  - production packers, for example, in the event of a leak through the annulus
- partially closed valves, depending on flow path
  - possible valves included in an intelligent completion
  - downhole safety valve
  - possible safety valves in the annulus
  - valves in the Xmas tree
  - valves (rams and preventers) in the BOP
  - internal valves in the work string
- work string with tools
  - WL
  - CT
  - jointed pipe
- possible plugs set as part of the activity.

The selection of blowout scenarios used must collectively cover the uncertainty range for blowouts in the activity under consideration. For each scenario, a conditional probability is set for its realisation in the event of a blowout. These probabilities must be determined on the basis of well-specific assessments. An analysis tool which enables such assessments for drilling is described in /8/. Historical data of relevance for such assessments are found in /9/-/11/. If historical data are applied directly, their relevance to the activity concerned must be explained. Should aspects of the activity indicate that such average values are not representative, the values must be adjusted in relation to an assessment of these conditions. See section 4.5.2. The sum of the scenario probabilities must be 1.

Descriptions of rate and duration calculations provided in the rest of this chapter assume that blowout scenarios have been defined, and focus on the calculations made for each scenario.

The combination of results at scenario level is described in section 4.5.3. Such combinations are necessary for achieving risk descriptions at higher levels. Examples include:

- scenarios for an activity
- activities with a well over one year
- wells for an installation over one year
- installations on a field over one year.

4.2 Presentation of uncertainty related to the course of a blowout

For a given blowout case, it can be assumed that enough measurements and calculations have been made to allow the flow rate to be presented subsequently as a function of time with a certain degree of precision. Figure 4.1 show an example. The total volume discharged corresponds to the area under the curve.

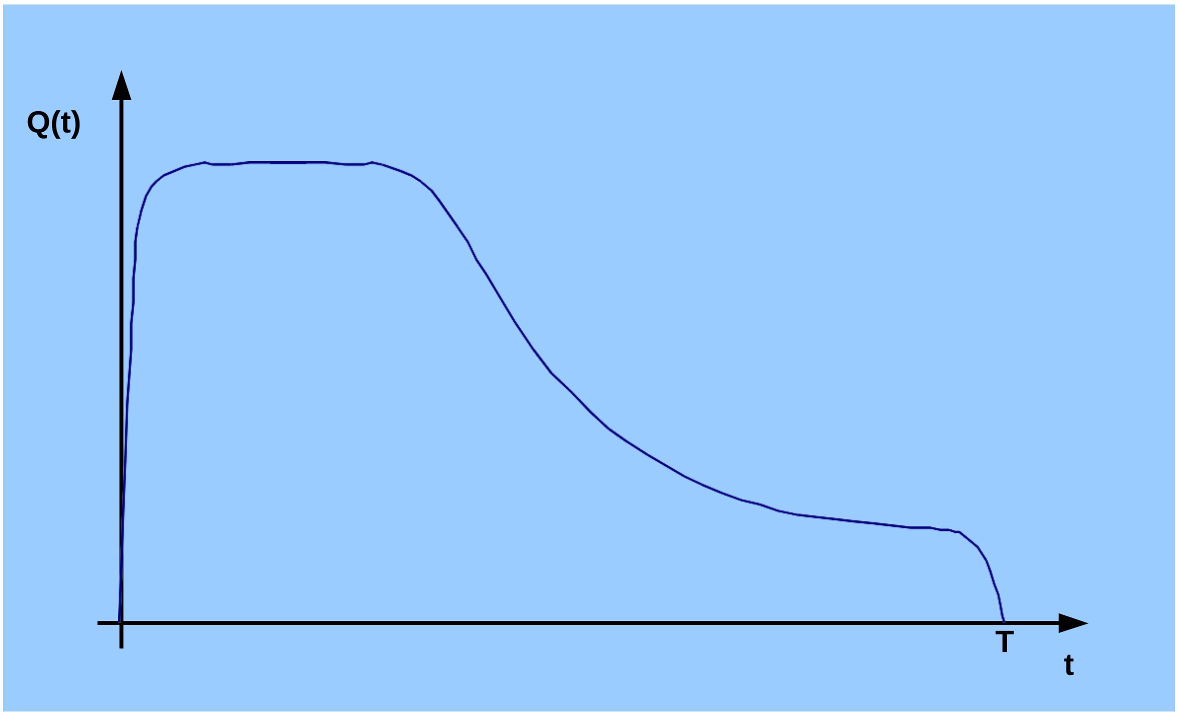

Figure 4.1 Example of the course of a blowout represented by the rate as a function of time.[3]

During the planning phase for an operation, when environmental risk analyses are conducted, it is virtually certain in most cases that a blowout will not occur. The uncertainty over the likelihood of a blowout is expressed as a blowout probability for the operation: P(blowout). Since the environmental risk is proportional to the blowout probability, this is a very important figure in the environmental risk analysis. As mentioned in the introduction, however, this uncertainty lies outside the subject dealt with here and no further mention is therefore made of it in this guidance. Attention is concentrated on predicting the course of events should a blowout occur. Even if it is assumed that “we know we’ll have a blowout”, conditional on a given scenario, substantial uncertainty will prevail in most cases about what its course will be. This can be presented, for example, in the way outlined in figure 4.2.

A risk description corresponding to the format in figure 4.2, which expresses uncertainty related to Q(t) continuously along the t axis, represents a complete and ideal presentation of uncertainty related to blowout rate and duration. However, such a description makes big demands on modelling and analysis.

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[3] This is generalised presentation which shows that the flow rate *can* vary over time. In many cases, this is very unlikely because of reservoir size in relation to flow rate. Where large reservoirs are concerned, the course of events will be more like the one presented in figure 4.3.

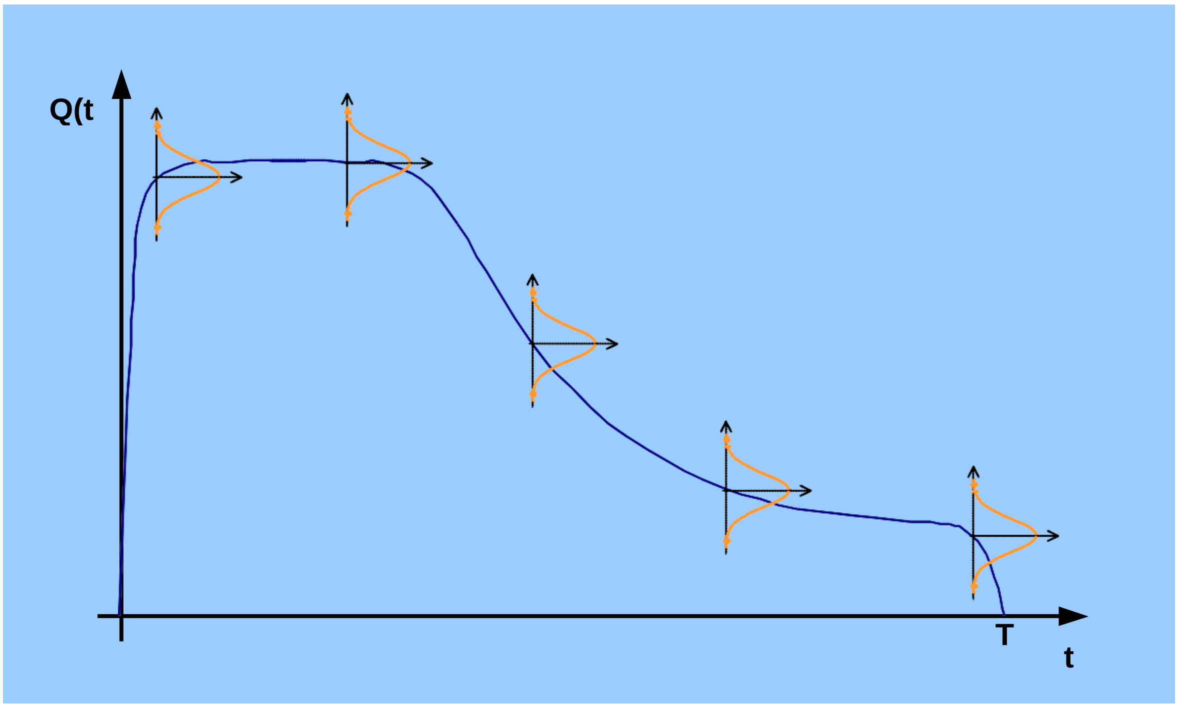

Figure 4.2 Idealised description of uncertainty related to the course of a blowout. (Generalised – identical normal distributions used for the sake of simplicity.)

An alternative presentation can be based on a simpler model, where the course of events is represented by the constant Q from t = 0 to t = T, and the uncertainty distribution is established for Q and T. If this approach is used, Q is equated with the maximum flow rate during the course of the blowout. Such a presentation is illustrated in figure 4.3.

Both presentations lay the basis for calculating the distribution of the total volume discharged.

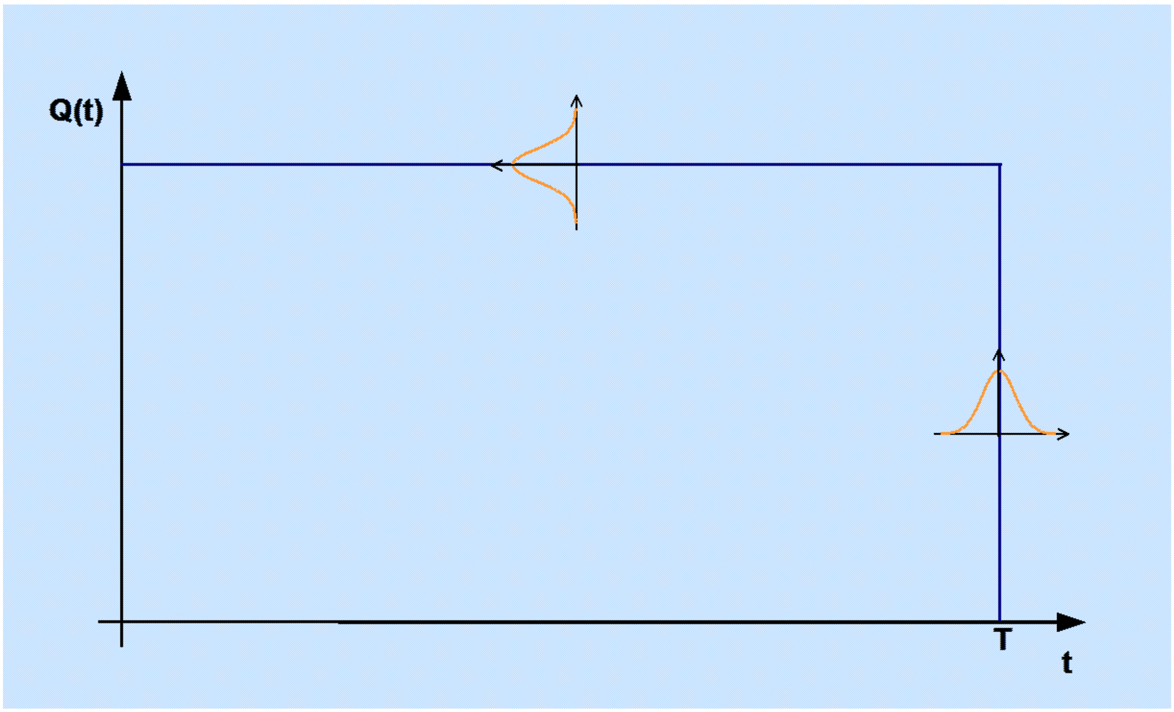

Figure 4.3 Simplified description of uncertainty related to the course of a blowout – flow rate independent of time and duration as a separate quantity. (Generalised – identical normal distributions used for the sake of simplicity.)

Conditions which primarily relate to assessments of rate and duration respectively are treated in separate sections below.

4.3 Blowout rate

The flow rate in the event of a blowout depends on a large number of factors. Many of these are uncertain in a planning phase, and the rate must therefore be regarded as an uncertain quantity. This is illustrated in figure 4.4.

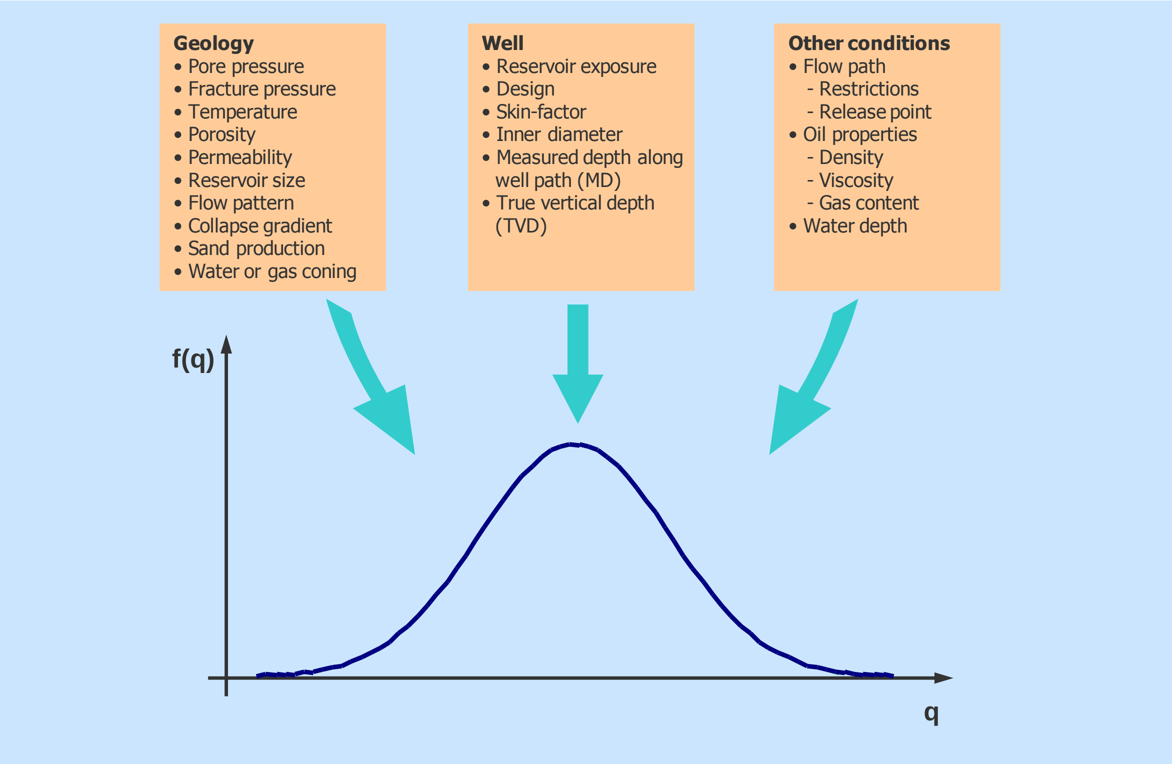

Figure 4.4 Factors affecting the blowout rate.

The relationship between flow rate and the factors listed in the figure are described in various areas of the physics, such as:

- fluid mechanics
    - models for multiphase flow in wells and pipelines
- well flow
    - flow from the closest part of the reservoir into the well
        - various models used in well and production technology
- reservoir technology
    - flow in porous media
        - flow from remote parts of the reservoir to the area where the well is located
- rock mechanics
    - maintaining the integrity of the open well section in the event of a strong flow and a pressure drop
        - models describing the disintegration of the well wall
        - models describing well collapse as the result of a global fall in reservoir pressure.

The models used for calculating rates must be recognised and tailored to the relevant well type. Where several different models can be used, an explanation must be provided for the choice of model together with the limitations imposed by the model and the tools used. Descriptions of the relevant models and equations can be found in the literature, and a number of computerised analysis tools are available on the market. See, for example, /12/ and /13/.

Calculating the value of the factors influencing the flow rate must be based on well-specific assessments. Uncertain quantities are represented by probability distributions. See section 4.5. Some of the factors could change over the course of the blowout. Account must be taken of such possible alterations to the parameters. Assessments of such changes could be an argument for distinguishing between an initial rate for the blowout and its subsequent course.

4.4 Blowout duration

Various mechanisms could cause a blowout to cease or be interrupted. These can be broken down as follows.

- *Active measures from the rig* – action taken by the facility's permanent crew or mobilised well control experts which results in control being regained over the blowout. A distinction can be made between:
    - mechanical shut-in of the well
    - killing with the aid of various types of mud and cement.
- *Bridging* – the blowout cease as a result of changes to flow conditions in the well without active human intervention. A distinction can be made between:
    - plugging or filling of the well with unconsolidated material or formation fragments
    - global collapse of the well.
- *Drilling relief wells* – one or more new wells are drilled into the lower part of the out-of-control well. The new well is used as a work channel for halting the blowout with the aid of various types of mud and cement.
- *Natural cessation* – conditions in the reservoir alter during the course of the blowout, so that the flow of oil ceases. A distinction can be made between:
    - pressure drop in the reservoir
    - pressure increase in the well
    - change in the flow medium because of water or gas coning.

In practice, a blowout may cease because of a combination of two or more of these principal mechanisms. A more detailed description of the mechanisms and literature references are provided in Appendix B.

It will not be possible during a planning phase to predict with certainty which of these mechanisms would ultimately lead to cessation. Nevertheless, an assessment of the duration, T, of a possible blowout can be based on the following expression:

$$T = \min(T_{\text{Active}}, T_{\text{Bridge}}, T_{\text{Relief}}, T_{\text{Cease}}) \qquad (3.1)$$

where T_{Active}, T_{Bridge}, T_{Relief} and T_{Cease} represent the time until the flow stops when the various mechanisms described above are considered in isolation. Determining uncertainty distributions for these and using equation 3.1 allows the distribution for T to be determined. Considerations which must be taken into account for the various cessation mechanisms are described below. Note that additional guidance on how to incorporate the effect of including a capping stack as a part of the blowout contingency system is described in the guideline amendment /1/.

T_{Active}

- Flow path and release point – can the blowout be halted by closing a valve or sealing a small opening which is easy to access?
- Platform well, mobile rig or subsea? The chances of succeeding with active measures are best when the wellhead is above the sea surface on a fixed facility.
- Type of operation – determines the type of work string, BOP and/or Xmas tree.
- Design of the wellhead deck, drilling area and rig, and opportunities for access with cranes and other equipment.
- Flow rate.
- Gas content.
- Company guidelines for various types of facilities.
- Time required to mobilise well control experts.

T_{Bridge}

1. *Bridging because of sand production*
   - The probability that significant sand production will occur – geological assessment.
   - Scope of sand production
     - described, for example, by the probability distribution for sand mass per standard cubic metre (scm) of medium produced.
   - Accumulation of sand in the well. This depends on the rate of production and on sand and oil properties
     - described, for example, by the probability that produced sand will remain in the well
     - preferably correlated with the rate model.
   - The above data are combined to find T_{Bridge} related to sand production on the basis of an assessment of the total quantity of sand required to halt a blowout.
2. *Bridging because of the accumulation of fragments detaching from the well wall*
   - The probability that this phenomenon will occur – geological assessment.
   - Further assessments similar to those for sand production in order to find T_{Bridge} related to this sub-mechanism.
3. *Bridging because of well collapse*
   - Rock mechanics model which takes account of
     - the collapse gradient for the reservoir
     - pressure drop
       - reservoir size, flow conditions and communication between zones
       - flow rate
     - preferably correlated with the rate model.
   - Probabilistic approach to identify T_{Bridge} related to well collapse.
4. *Bridging because of hydrate formation*[4]
   - Probability that the necessary combination of pressure and temperature will be present.
   - Probability that sufficient quantities of gas and water will be present.

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[4] Hydrate as a cessation mechanism is open to discussion, and specific reasons must be provided if this is given weight in the analysis.

- Assessment of the probability of full plugging, given hydrate formation against the background of the cross-sectional geometry of relevant flow paths.
- The above data are combined to find T_{Bridge} related to hydrate formation.

5. *Total T_{Bridge} is calculated by combining the results of items 1-4 above.*

T_{Relief}

1. *Time to mobilise*
   - Time taken to decide to drill one or more relief wells.
   - Time taken to mobilise a rig to the location (typically 14 days)
     - agreements with nearby rigs
     - time to terminate possible jobs under way
     - time for possible equipment upgrades – eg, new BOP[5]
     - time to choose the location for spudding the relief well and planning the well path
     - transit to the location
       - distance to the location
       - possible opportunity to use one's own rig to begin drilling a relief well
     - mooring and drilling preparations.
2. *Time required to drill the well*
   - Depth.
   - Rate of penetration (ROP).
   - Angle.
   - Number of casings.
   - Extra time required to drill in towards the part of the well which is out of control
     - including time for magnetic position correction (ranging) – 10 days is not unusual
     - probability of a satisfactory intersection or possibly of a new attempt.[6]
3. *Time required for the actual kill operation*
   - Strategy for the kill method.
   - Probability of a successful kill on the first attempt.
   - Extra time if a new attempt is required or more than one well must be drilled from the start.
4. *Total T_{Relief} is calculated as the sum of the sub-results from items 1-3 above.*

T_{Cease}

1. *Cessation because pressure differences between reservoir and well are equalised*
   - Pressure drop in the reservoir close to the well
     - reservoir size, flow conditions and communication between zones
     - flow rate
     - preferably correlated with the rate model.

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[5] Some kill operations will call for non-standard equipment, such as high-pressure pumps, high-capacity kill and choke lines, and mud storage capacity. Such equipment may have long delivery times.

[6] Magnetic positioning utilises the steel in the drill string or casing as the reference for guiding the bit. The position of the casing and drill string determines which point on the well path is being targeted. If it proves necessary to drill high above the inflow point – because the string has been wholly or partly pulled out, for example – the kill operation would be made more difficult in most cases.

- Take account of pressure change in the well from the loss of artificial lift (gas lift or pumps).

2. *Loss of the oil phase in the blowout medium because of water or gas coning*
- Probability of water or gas coning – geological assessment
    - thickness of the oil layer
    - viscosity of the oil
    - reservoir flow properties horizontally compared with vertically
    - production rate
    - preferably correlated with the rate model.

3. *Total T_{Cease} is calculated by combining the results from items 1 and 2 above.*

4.5 Handling uncertainty in the calculations

Results from the calculations outlined so far in this chapter provide a description of uncertainty related to blowout rates and duration, assuming that a specific blowout scenario occurs in the future. See section 4.1. The uncertainty is described with the aid of probability distributions.

The quantitative analysis involves extensive use of models, the determination of a number of probabilities and probability distributions as input values for the calculations, and complex probability calculations. The basis principles for these elements in the analysis are described below.

4.5.1 On the use of models

In this document, “model” means a mathematical description of the relationship between real, observable quantities. These can be *physical quantities*, such as length, volume, mass and time, and *events*, like “well collapse”, “valve closes” or “relief well encounters the path of the well out of control”. A model can be expressed by:

$$Y = g(\mathbf{X}),$$

where Y is the quantity being analysed (such as rate), **X** is the vector of the quantities assumed by the model to influence Y, and g is the mathematical relationship between Y and **X**.

An example of a model is the expression (3.1) presented earlier in this chapter:

$$T = \min(T_{Active}, T_{Bridge}, T_{Relief}, T_{Cease}).$$

Expressions which describe a probability, or a probability distribution are not models. Assume X_1 is a physical quantity, such as a pressure, measured in bar and with a normal distribution, X_1 ι N(500, 20) . The expression for the probability density of X_1,

$$f(X_1) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{1}{2}(\frac{x-\mu}{\sigma})^2} ,$$

is therefore not a model. Probabilities describe the uncertainty related to a real quantity, in this case X_1, which is an assessment, and do not express the relationship of that quantity to other physical quantities as models do. Models are simplified descriptions of real causal relationships, but not so simplified that results from using them fail to create confidence when decisions need to be made.

The purpose of using models in a risk analysis is to express the uncertainty about a quantity Y through other quantities, $\mathbf{X}$, about which more is known. Uncertainty related to $\mathbf{X}$ is expressed through a set of probabilities and probability distributions, and is transformed to a probability or distribution related to Y with the aid of the model structure and the rules for probability calculus.

More on using models in risk analyses can be found in /15/, section 5.2 and /16/.

4.5.2 Determining probabilitets and probability calculations

A number of probabilities and distributions must be determined as input to the quantitative analysis. Some requirements are presented below for this process and for the actual calculation, where the input values are used to calculate the uncertainty related to rates and durations.

1. All quantities in the models are basically regarded as uncertain and thereby described by probabilities (events) or probability distributions (continuous quantities). Quantities which can be regarded as certain after an assessment, or where it can be argued that the uncertainty makes an insignificant contribution to uncertainty in the blowout course, can be regarded as deterministic and are represented by a specific value.
2. Probabilities must be determined on the basis of an overall well-specific uncertainty assessment based on information in the form of
    - available, relevant experience data
    - expert judgement.

    If the information basis is regarded as weak, further modelling should be considered.
3. Specified probabilities must as far as possible be neutral – in other words, not conservative.
4. The information basis underpinning a probability value must be documented and arguments presented to establish that it is adequate.
5. Accumulating specified probabilities in models in order to obtain an uncertainty description at a higher level must
    - be conducted in line with the rules for probability calculus and combinations so that
        - dependencies are reflected
        - the calculations are neutral and do not give conservative values.

More on determining probabilities can be found in /15/ with references and in chapter 5.

4.5.3 Collating rate and duration calculations for various scenarios and the scope and level of activities

Attention in this chapter has so far concentrated on quantification of uncertainty related to the blowout course, assuming that a specific blowout scenario occurs in the future. See section 4.1.

An environmental risk analysis requires risk descriptions from several scenarios to be collated in a bigger picture corresponding to the activities at which the analysis is directed and to the applicable acceptance criteria. This can involve the following.

1. Collating several scenarios in order to establish the risk picture for the blowout course for a single *operation* or a defined number of similar operations.
    - Results from the calculations at scenario level are weighted with the probabilities for the occurrence of the various scenarios, assuming a blowout.
2. Collating several operations in order to establish the risk picture for a *well* during a specific period, such as one year.
    - Results at the operational level are weighted in relation to the blowout probabilities for the various operations.
3. Collating several wells in order to establish the risk picture for an *installation*.
    - Results at the well level are weighted in relation to the blowout probabilities for the various wells.
4. Collating several installations to establish the risk picture for a *field*.
    - Results at the installation level are weighted in relation to the blowout probabilities for the various installations.

These calculations are performed in line with point 5 in the previous section.

5 GUIDANCE

The purpose of the reference methodology for calculating the uncertainty related to the blowout course outlined in chapter 4 is to describe an ideal solution for such calculations and to provide the basis for making various practical adjustments. The guidance in this chapter is directed at the way the various parts of the reference methodology can be amended in order to simplify the work, and at the requirements for underpinning and documenting such simplified analyses.

The reference methodology represents a very detailed analysis which will, in most cases, be unnecessary for providing sufficient decision support in relation to the acceptance criteria. For certain analyses, however, a detailed analysis will be desirable. Simplifying the analysis has two main consequences for the use of the analysis results.

1. Higher risk value (higher flow rates and durations) as a result of introducing a conservative element when simplifying.
2. A reduced level of detail in the analysis reflects well-specific conditions poorly. An analysis of a more generic character will have a lower utility value for decision support where input is required about how risk can be reduced. The environmental risk analysis as a whole can still be used to support the introduction of impact-reducing measures in the form of well design or oil spill preparedness, but will provide little or no support for measures to reduce rates and durations.

Two conditions can consequently be established which ought to motivate a thorough analysis close to the level of detail outlined in the reference methodology.

1. Activities with a high blowout risk in relation to the acceptance criteria, where a strong conservative element could in itself push the calculated level of risk above the acceptable level specified by the acceptance criteria. Such activities could be characterised by one or more of the following.
    - Conditions which indicate a high blowout probability – a difficult well operation in terms of pressure control and a high probability of a well kick
        - uncertain pore and fracturing pressure
        - narrow or uncertain pressure margin
        - uncertain reservoir geometry
        - unknown area.

      Examples of operations which could be characterised by such conditions include drilling in high pressure, high temperature (HTTP) reservoirs, exploration drilling and drilling in depleted reservoirs.
    - Conditions which indicate a high blowout rate and/or duration
        - high reservoir pressure
        - good flow conditions in the reservoir
        - large well diameter
            - a large diameter planned in the reservoir
            - drilling sections which were planned to be terminated above the reservoir unintentionally into the reservoir
        - long reservoir section
            - thick reservoir zone

        - horizontal well
        - casing programme
    - poor conditions for rapid and secure drilling of a relief well and killing
        - long mobilisation time
        - difficult drilling conditions
        - poor pressure margin – because of HPHT conditions, depletion or a risky casing programme, for example
        - large well diameter.
- The activity will take place in an environmentally sensitive area
    - short distance to shore
    - unfavourable currents or wind conditions
    - vulnerable resources on the beach or in the sea.

2. A good level of detail in the analysis allows well-specific data to be reflected. An analysis of a more generic character will have little or no utility for decision support where the aim is to reduce risk – in an Alarp process, for example.

However, it must be emphasised that, for a substantial proportion of environmental risk analyses covering operations characterised, for example, by

- considerable distance from the shore
- good knowledge of geological conditions
- standard operations, or
- less environmentally sensitive areas,

very simplified analyses can be adequate for providing the desired decision support.

Sections 5.1-5.5.3 correspond with the equivalent sections in chapter 4, which describes the reference methodology. The discussion here covers the way various aspects of the analysis can be simplified.

5.1 Definition of blowout scenarios

The amount of work devoted to rate and duration calculations for a well is more or less proportional to the number of blowout scenarios defined.

If scenarios are excluded, this must be done in such a way that the resulting selection of scenarios with associated probabilities for incorporation in the analysis gives a more conservative picture than before the exclusion. This means that scenarios with:

- small well diameters are excluded before scenarios with large well diameters[7]
- short open hole sections/limited exposure to the reservoir are excluded before scenarios with long open hole sections/greater exposure
- release points and flow paths which give a low rate are excluded before scenarios with release points and flow paths which give a high rate[8]

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[7] This will be conservative in most cases.

[8] This will be conservative as long as the low-rate scenario does not involve a substantially longer time for killing with the aid of a relief well.

- substantial restrictions are excluded before scenarios with limited or no restrictions
- etc.

Probability related to relatively favourable scenarios which have been excluded are transferred to more unfavourable scenarios being taken into account.

Note that, in some cases, it can be difficult to decide whether a scenario is more conservative than another unless calculations are conducted at a certain level of detail. This may reflect both well/workstring geometry and reservoir fluid. On some occasions, for example, a well/workstring geometry with a smaller annular area may give a higher rate than a more open one. Similarly, a higher gas-oil ratio (GOR) can lead to more oil on the sea than a heavy crude. That makes it important to apply available well-specific knowledge along with expertise on well physics when selecting scenarios.

5.2 Presentation of uncertainty related to the course of a blowout

Chapter 4.2 describes a simplification which involves making the flow rate, Q, independent of time, so that rate and duration are treated as independent quantities. See figures 4.2 and 4.3. The presentation can be simplified further as follows.

1. Discretise the probability distributions – in other words, divide the uncertainty range for rate and/or intervals with the associated probability, presented in a table, histogram or the like. See table 5.1.
2. Present rate and/or duration with a simple deterministic value. This must then be conservative, where a probability that a possible blowout will yield a higher rate/duration is substantially lower than ≤ 0.5. A broadly accepted choice, for example, is to use a probability of ≤ 0.1 – in other words, using the 90th percentile or higher. Arguments for the choice of percentile must be made and documented.

Arguments for using the 90th percentile are:

- use of the 10th and 90th percentiles together with a central value (expected or median) is a known format for simplified probability distributions among engineers, and is therefore simple to apply
- the 90th percentile is sufficiently conservative to avoid discussion about this.

Similar formats can also be used to present uncertainty related to the total volume discharged.

Table 5.1 An example[9] of the format for the discrete presentation of uncertainty related to blowout duration – topside and subsea blowouts.

Duration	**Two days**	**15 days**	**40 days**
Topside	77%	18%	5%
Subsea	60%	24%	16%

5.3 Blowout rate

Given a selection of blowout scenarios – see section 5.1 – simplifications will first and foremost be relevant in three areas related to rate calculation.

1. Selection and use of the flow model.
2. Assessment and quantification of uncertainty related to the quantities in the flow model.
3. Method for quantifying flow-rate uncertainty by propagating uncertainties related to the quantities in the flow model.

Items 2 and 3 are covered in section 5.5.

Several options with varying degrees of refinement are available when selecting models for rate calculation. Furthermore, having selected a model, the analyst will consider possible simplifications by making assumptions and establishing preconditions. Simplifications are often also involved when considering whether a model is actually applicable to the well in question. When selecting a simple rather than a more detailed model, adaptations related to the area of application, or other simplifications in the form of the assumptions made and so forth, the choices made must give rates which are at least as high as when choosing a more refined model or when no simplifications are made.

Should rates be determined on the basis of a reference well where rate calculations have already been made, it must be documented that this yields rates which are as least as high as a specific assessment of the relevant well. The justification for using a reference well must be based on a comparison between the two wells in terms of conditions affecting the rate. See figure 4.4.

5.4 Blowout duration

The reference methodology for calculating duration is based on detailed individual modelling of the time to cessation with four mechanisms – T_{Active}, T_{Bridge}, T_{Relief} and T_{Cease}. See section 4.4. Refer also to the guideline amendment /1/ on incorporating the effect of a capping stack as a potential stop mechanism. This approach means that uncertainty related to duration is calculated from the uncertainty inputs related to quantities at a detailed causal level in models related to the four mechanisms.

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[9] Note that these figures have been made up for the purpose of this example and are not intended for direct use in actual analyses.

An alternative simplified approach, widely used in practical analyses today, involves more or less direct use of historical data in the analysis of one or more of the four mechanisms. Such data represent an average of blowouts which have occurred during a certain period, and often across relatively extensive geographical areas. If such an approach is used, the extent to which the data are representative for the relevant operation must be determined. An assessment of this must be based on a well-specific assessment of the factors listed for the various mechanisms in Appendix B. If the data suggest that these are conservative for the relevant well – in other words, yield longer durations than a well-specific assessment indicates – this simplification is acceptable. On the other hand, should the data be found to be optimistic, a more detailed approach based on the principles described in section 4.4 will be necessary.

A ranking of the four cessation mechanisms described is provided below to determine whether an approach based on the reference methodology principles should be given priority.

1. Drilling a relief well
    - Drilling-, operation- and organisation-specific conditions can have great significance and can be quantified on the basis of relatively simple assessments.
    - Do too many parallel operations in an area have a big influence on uncertainty related to the duration of a possible blowout?
2. Natural cessation
    - With the exception of exploration drilling, it will be relatively simple in most cases to predict how far this mechanism is relevant.
    - Can have crucial significance for low-productivity wells, such as producers driven by artificial lift.
3. Bridging
    - Fairly reservoir-specific, but can be difficult to quantify on the basis of modelling.
4. Active measures from the rig
    - Heavily dependent on installation and well type, but can be difficult to quantify on the basis of modelling.

See Appendix B for further details.

5.5 Handling uncertainty in the calculations

5.5.1 Use of models

Simplifications made through the selection of models must be neutral or influence the results in a conservative direction.

5.5.2 Determining probabilitets and probability calculations

If probabilities are determined on the basis of less detailed assessments – in other words, available data or other background knowledge are deliberately not utilised – the probability values set must affect the results in a conservative direction compared with a more detailed assessment.

The reference methodology indicates extensive use of probability distributions to describe uncertainty related to continuous quantities in the models. These types of quantities lie at a detailed causal level – an example would be pore pressure in an exploration well. Little relevant experience data is available for these quantities which could form the basis for determining distributions. Expert assessments will thereby represent an important part of or the whole basis for determining the distributions. Some simple distribution types which would be suitable in this context are illustrated in figure 5.1.

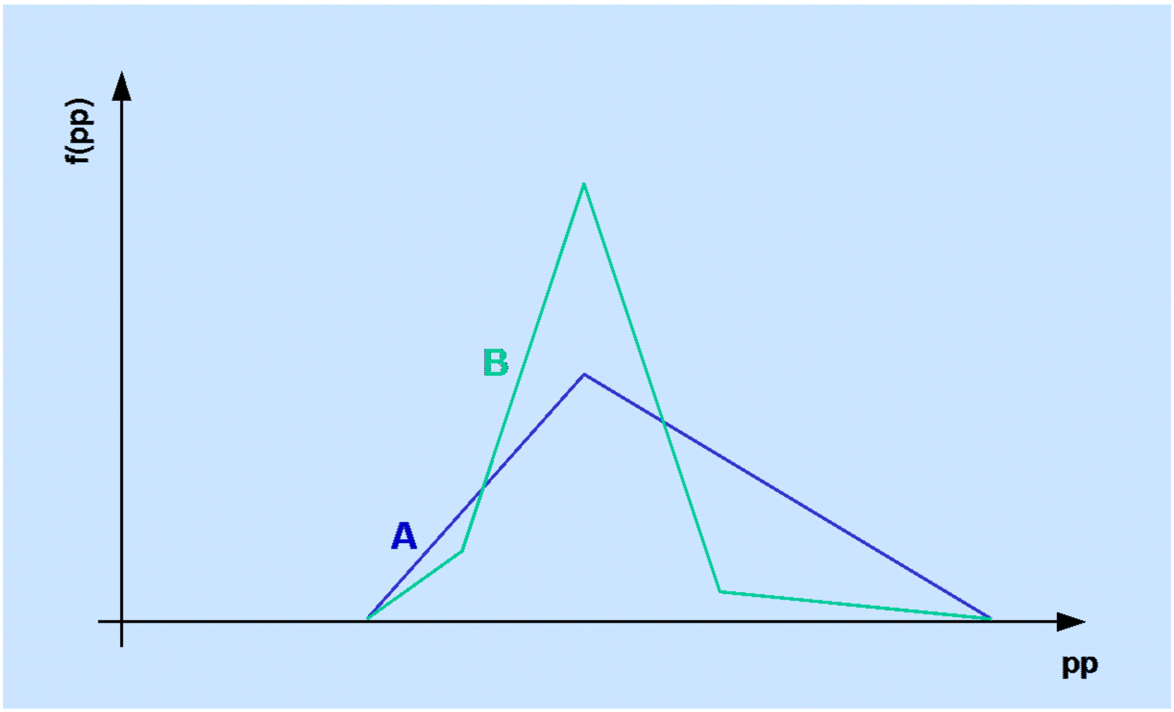

Figure 5.1 Examples of types of probability distributions (densities) suitable for determining distributions with a strong element of expert assessment. For instance, uncertainty related to pore pressure (PP) is represented by A: triangular distribution, B: five-point stepped linear distribution. See also figures D.4 and D.5.

A possible simplification with regard to determining distributions is to represent the input quantities with deterministic values. These should then be conservative, with a probability of ≤ 0.1 that the outcome for the relevant size is greater than the specified value.

When expert assessments form a significant part of the basis for determining probabilities, it is critically important that personnel with relevant expertise are involved in the process. Typical disciplines with relevance for assessing quantities in rate and duration calculations include:

- geologists
- drilling/well experts
- experts on reservoir or production technology
- well control specialists.

Achieving a theoretically correct accumulation of probabilities in the models for calculating final rate and duration distributions is difficult and resource-intensive in practice. Monte Carlo simulation is a method which provides sufficient precision with a suitable number of iterations, and which makes it possible to account for interdependence in a simple way. Monte Carlo simulation is described in textbooks on stochastic modelling, risk analysis and statistics. See, for example, /15/, page 18. If other simplifications are made, these must be neutral or contribute to conservative results. Assessments of the effect of the simplifications on the results must be documented.

5.5.3 Collating rate and duration calculations for different scopes and levels of activity

For the definition of blowout scenarios, see section 5.1.

Collating rate and duration distributions for different operations in order to establish the risk picture for a well over a period must be based on calculated distributions for all relevant operations. The calculation can be simplified by also using the results for one operation with operations which have lower rates/durations. Assessments which demonstrate the likelihood that this does not give more favourable results must be documented.

A corresponding simplification can be achieved by collating rate and duration distributions for:

- different wells in order to establish the risk picture for an installation
- different installations in order to establish the risk picture for a field.

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APPENDICES

A. General introduction to loss of well control in drilling and well activities – causal mechanisms for blowouts – focus on drilling operations
B. Combating and stopping a blowout – four mechanisms
C. History – overview of earlier work in this field within and outside the ambit of Norwegian Oil and Gas, current regulations and operating company practice
D. Calculation examples

A LOSS OF WELL CONTROL

A blowout means that an uncontrolled escape of formation fluid from a reservoir to the sea or the air has occurred. Examined more closely, this term becomes more of a collective designation for a large group of phenomena which display considerable variation. Several important factors, including the following, mean that blowouts can differ considerably in character.

- *Flow medium* – whether the outflow comprises oil, condensate, gas, water or a mixture of these media is crucial for the potential harm which a blowout can cause to people, the environment and material assets. Since this document deals with the environmental consequences, its attention is confined to oil or condensate blowouts. The viscosity, density and gas content of the medium affect how easily it flows through the reservoir and up the well.
- *Flow rate* – the strength of the oil or condensate flow has a direct influence on the total volume released and thereby on the scale of potential damage to the environment. In most cases, the flow rate will decline sharply in a relatively short time.
- *Release point* – the flow of formation fluid can reach the sea between the seabed and the surface, or the air between the sea surface and the topside of the facility involved in the well activity. Whether the fluid goes to water or air has a big impact on the flow rate and the spread of the pollution. Another category is an underground blowout, where the formation fluid flows from the reservoir to another sub-surface zone. Since such incidents do not have consequences for the natural environment, they are not discussed in this document.
- *Duration* – along with the flow rate, the duration of a blowout determines the total quantity released and the scope of possible harm. In certain cases, a blowout can be halted in its initial phase by simple operator interventions – within a short time as a result of changes in well or reservoir conditions, or somewhat later following the use of more extensive well control measures. Changes in well and reservoir conditions can cause a blowout to cease. The time it takes to mobilise a facility and drill a relief well is often taken to be the maximum duration of a blowout.
- *Flow path* – the channel which the formation fluid flows through from the reservoir to the release point. Typical flow paths include an open hole – in other words, a well where the drill, operation or production string has been pulled out – the annulus between the string and the casing, the string itself, or a continuous channel between the casing and the formation up to the surface.
- *Restrictions* – partly closed valves. well equipment or fragments from the formation can limit the potential flow along a path. Restrictions can arise or be broken down during the course of the blowout.
- *Reservoir* – the size of the reservoir which provides the source for the blowout is the ultimate limitation on the quantity of formation fluid released. Pressure and flow conditions in the reservoir have a strong effect on the flow rate.
- *Reservoir exposure* – determined by how much of the well length extends into the reservoir, the well diameter and the properties of any completion equipment installed.

Where the occurrence of a given blowout is concerned, most of these conditions will be determined by the well's design and geometry as well as the causal mechanism which has given rise to the incident. Assessing the scope and consequences of a blowout therefore calls for insight into how such an event could occur with various types of well activities.

At least two independent well barriers are required for all drilling activity on the NCS. See sections 85 and 48 of the activities and facilities regulations respectively /2/. An intact well barrier is intended to prevent the uncontrolled escape of formation fluids to the surroundings. A blowout therefore means that both barriers have failed. Barrier arrangements vary between different well activities. Some general characteristics of drilling activities, such as barrier arrangements, failure mechanisms and the way these affect the scope of a blowout, are described briefly below. The intention is to include corresponding descriptions for other types of operations, such as completion, production, well intervention and well workovers, in a later revision of this document.

A.1. Drilling

Conventional drilling utilises a drill string which comprises lengths of steel pipe screwed together. These tubes are about 10 metres long and have a significantly smaller diameter than the drill bit. The string is normally rotated during drilling by a power source on the rig (normally a top drive). Mud is pumped down through the hollow centre of the pipe, out through nozzles in the bit and back to the surface up the annulus surrounding the string. The formation being drilled is exposed at the bottom of the well and comprises the outer wall of the annulus. This is known as the open hole section. When drilling in formations where oil or condensate blowouts might occur, several lengths of casing will already have been set and cemented to the formation between the open hole section and the wellhead. The casing forms the outer wall of the annulus in this part of the well. When using mobile floating facilities, the wellhead is usually installed on the seabed. In these cases, the string is encased in a riser between the wellhead and the rig. The riser then forms the outer wall of the annulus between the seafloor and the rig. On fixed installations, the wellhead may be installed topside so that the casing also forms the outer wall in the uppermost part of the well until the low pressure riser is encountered. The latter extends from the wellhead to the drill floor. Different arrangements are illustrated in figure A.1

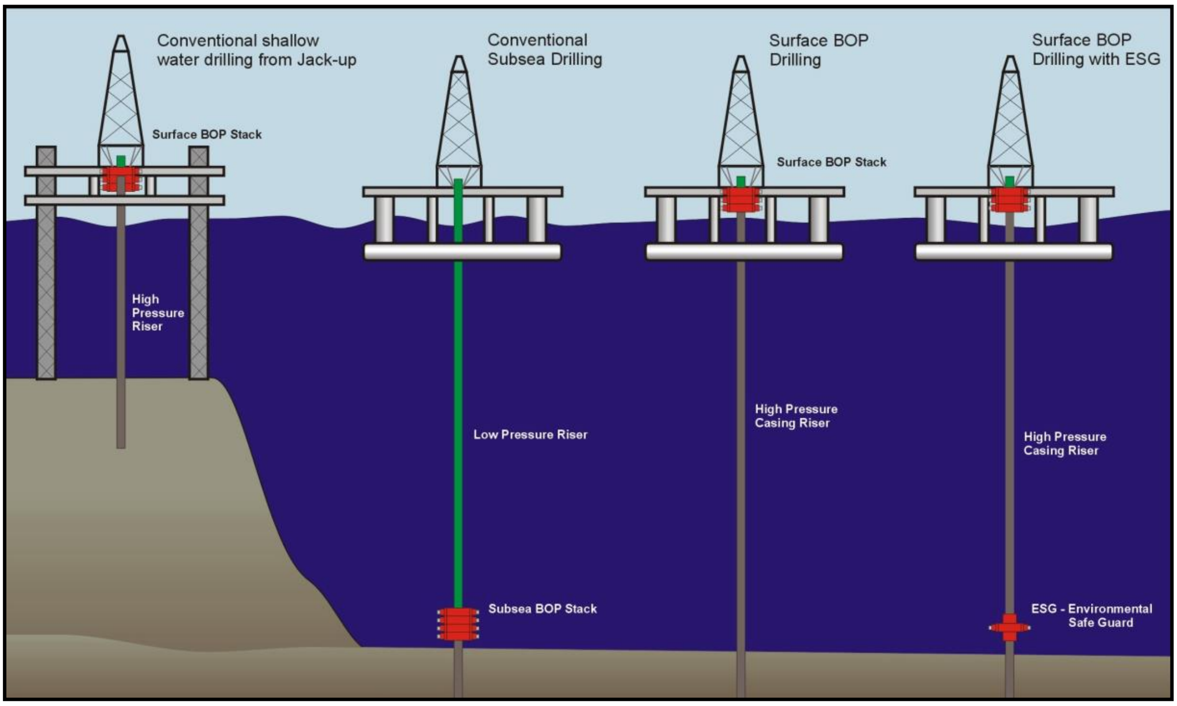

Figure A.1 Various arrangements of BOP, casing and riser. The two examples on the left are the ones most commonly used on the NCS.

In addition to playing a role in lubrication, cooling and transport of drill cuttings out of the well, the column of mud serves as a barrier against a blowout. The density of the mud must be tailored to ensure that hydrostatic pressure at the bottom of the hole is higher than formation pressure. That prevents formation fluid from entering the well.

The first stage in the cause-consequence chain which leads to a blowout during drilling is that the overpressure against the formation is lost, with a subsequent inflow of formation fluid. Such an influx is known as a kick. As soon as a kick has been observed, the well will be shut in by closing the BOP and a well control operation initiated to remove formation fluid from the mud column and re-establish overpressure against the formation. The BOP forms the secondary well barrier together with the wellhead and the casing permanently cemented to the formation. A blowout can only take place if the mud column and the secondary well barrier both fail. The precise failure mechanism is significant for the blowout rate. Some examples are described below.

A kick occurs if mud pressure falls below pore pressure at a point in the operation. Some principal causes are as follows.

1. Higher pore pressure than expected.
2. Lower mud pressure than intended.
3. A temporary reduction in mud pressure for operational reasons.
4. Combinations of 1-3.
5. Loss of mud to the sea or the formation, and a reduced hydrostatic column.

If pore pressure is higher than expected, a kick is likely to occur when the well is drilled into a high-pressure area with insufficient mud pressure. That means the drill string will be in the well and impose some restriction on the blowout flow rate. Such a kick will often occur soon after the reservoir has been penetrated, which means reservoir exposure is likely to be limited.

The most important contributor to item 3 above is the under pressure (swab pressure) which arises beneath the bit when the drill string is being pulled from the well (tripping out). Generally speaking, trips are only planned after drilling of a well section has been completed. In most cases, the first trip out of the well from a completed reservoir section is therefore the first such operation after penetrating the reservoir. Swabbing in a kick therefore often involves substantial reservoir exposure.

With the other principal causes of a kick, the degree of reservoir exposure will vary greatly. Detailed descriptions of causal mechanisms for well kicks can be found in textbooks on drilling and well control, and in /6/ and /7/.

How the secondary barrier fails can also be significant for the blowout rate. Two failure categories can be distinguished.

1. A failure in the BOP when shutting in the well following the detection of a kick or during a well control operation.
2. A failure in the actual well control operation leading to an uncontrolled pressure build-up, which breaches one of the elements in the secondary barrier.

The BOP comprises a set of valves (preventers and rams) which can seal off the annulus or cut the drill string and shut off the whole open cross-section of the hole. If the BOP fails to seal the well, one or more of the valves will in most cases be partially closed and thereby serve to restrict the escape of fluid from the well.

If the secondary barrier is lost because of overpressure, the element which fails will affect both flow path and rate. A pressure build-up will be greatest in the upper part of the well. Should a breach arise in the form of limited leakage through a BOP valve or at the joint between riser, casing or wellhead elements, this could be favourable in terms of flow rate compared with a full breach in these components.

In the event of a blowout with a substantial flow and a release point topside on a mobile floating facility, the riser will be disconnected at the seabed and the rig moved to a safe area. The flow of oil thereby acquires a new release point at the seabed. How far that will affect the flow rate is determined by the water depth and changes to restrictions in the well. Flow resistance in the well could be substantially reduced if controlled disconnection from the riser fails, so that the wellhead is damaged, or the drill string gets drawn out of the well.

B FIGHTING AND STOPPING A BLOWOUT

A more detailed description of the four main mechanisms for fighting or stopping a blowout, described in sections 4.4 and 5.4, is provided below[10].

B.1. Active measures from the rig

This category of mechanisms covers all action taken by the installation's permanent crew or mobilised well control experts which results in the blowout being brought under control. Two principal categories of such measures can be distinguished.

1. Mechanical sealing (capping) of the well.
2. Killing with the aid of mud and possibly cement.

In most cases, capping involves installing a new wellhead on top of the existing one. This can either in itself contribute to shutting in or lay the basis for entering the well and killing it with mud or cement. Depending on the type of operation, capping can also involve closing one or more valves in the well's permanent barrier system, such as:

- one of the BOP valves
- valves in the Xmas tree
- valves in the drill or operation string
- downhole valves.

This could be a possibility, for example, if one of the causes of the blowout was a failure in the valve's control system which subsequently proves to be repairable.

The ability to run a work string or having one already in place is a precondition for pumping mud down the well. A distinction can be made between hydraulic or dynamic killing. In the first case, a heavy mud is used which provides sufficient hydrostatic pressure to stop the flow from the reservoir. Dynamic killing involves circulating mud in the well at high pumping rates, so that the frictional pressure loss makes a substantial contribution to the counterpressure against the reservoir. A killing operation can also be a combination of these two methods.

Bullheading is another approach. In principle, this involves pumping liquid at high rates and under high pressure through the BOP's choke and kill lines. That presses the formation fluid back into the formation and eventually fills the well with sufficiently heavy kill mud. This method consequently again requires the ability to pump with sufficient rates and pressure to drive more mud into the well.

Cement can be used in a kill process either by filling all or part of the well with this material, in the same way as with a kill mud, or by driving cement slurry into the formation.

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[10] The use of a capping stack is a relatively new measure to stop a subsea blowout. The measure is briefly presented in the guideline amendment /1/.

In most cases, the prospects for success with active measures from the rig will be considerably improved if the blowout rate falls after a time. Other favourable factors include a low proportion of gas in the blowout medium and good access to the wellhead and other relevant work areas with cranes and similar critical equipment.

B.2. Bridging

Bridging is a collective term for mechanisms which alter downhole conditions so that the flow ceases. The following can be distinguished.

1. Accumulation of unconsolidated material in the well to block the flow.
2. Well collapse.
3. Formation of a hydrate plug in the flow path.

Unconsolidated materials can derive from sand accompanying formation fluid out of the reservoir (sand production) or be loosened from the well walls by the production flow or as a result of stress changes in the formation surrounding the well.

Relatively unconsolidated sandstone reservoirs with good permeability can give rise to substantial sand production. Depending on flow rates, the sand can accumulate over time in the well to restrict and eventually halt the flow. If blowout rates are high, however, the sand will accompany the oil stream out of the well.

A combination of a brittle formation, friction from the fluid flow along the well wall and stress changes in the well wall could cause formation fragments large and small to flake off and plug the well.

Should the drainage of formation fluid during a blowout cause formation pressure to fall to a level below the formation’s collapse gradient, the well may collapse or implode. The flow will then be sharply reduced or cease completely. Factors which could contribute to well collapse include:

- high flow rates which yield rapid drainage of the reservoir and pressure drop
- a small reservoir or poor communication between various reservoir areas, which gives rapid pressure drop per unit volume of liquid drained
- a high collapse gradient (loosely consolidated formation).

Hydrate can form if the flow medium contains both gas and water as well as oil, and if it passes through an area with relatively high pressure and low temperature. If the flow path is also relatively narrow, hydrate formation could halt the blowout. Hydrate as a cessation mechanism is open to discussion, and specific reasons must be provided if this is given weight in the analysis.

B.3. Killing a blowout via a relief well

A relief well will be spudded where it is difficult for various reasons to conduct effective kill measures from the rig. This is drilled in towards the bottom of the blowing well. If effective communication can be established between the two wells, control could be restored over the blowout with the aid of dynamic and hydraulic kill methods. See B.1. Killing blowouts with the aid of relief wells is described in such sources as /17/.

Drilling a relief well is a time-consuming business. Sub-activities which contribute to the duration of such operations include:

- allocation of a rig
- mobilising and mooring the rig
- directional drilling and advanced control down towards the lowest part of the blowout well which contains metal (casing or drill string)
- the actual kill operation.

B.4. Natural cessation of a blowout

In some cases, the changes caused by a blowout to pressure and flow conditions in the reservoir may in themselves lead the flow to cease completely or convert an oil stream to a water and/or gas flow.

The wellstream depends on the pore pressure in the reservoir being higher than pressure at the bottom on the well. Should the pressure underbalance be marginal to begin with and the reservoir of limited size, the drainage caused by the blowout may equalise the pressure between well and reservoir.

Another variant of this mechanism is a blowout from production wells driven by and depending on gas lift. In such a well, gas is pumped into the production stream some distance down in the wells. Bubbles in the gas expand as they rise and reduce the average density of the production stream. That in turn lowers the hydrostatic pressure at the bottom of the well, permitting inflow from the reservoir. In the event of a blowout, the gas supply would be discontinued, and the flow eventually cease.

If gas or water coning is a relevant mechanism in a well, this phenomenon could convert a blowout which initially conducts oil to the surface into a pure gas and/or water discharge. Three phases lie one above the other in the reservoir – gas on the top, water at the bottom and oil in between. The thickness of these layers and the extent to which all are present vary from reservoir to reservoir. When producing from the oil layer, a local pressure reduction arises in that part of this zone which is closest to the well. Depending on such factors as:

- thickness of the oil layer
- viscosity of the oil
- reservoir flow properties horizontally compared with vertically
- production rate,

the interface between the three fluid layers during production will differ from the original in the vicinity of the well. The water phase is pulled up and the gas phase down. With vertical wells, these changes form cones centred in the well. That increases water and/or gas cuts during oil production. Concern about water/gas coning could govern the design of the well path for producers and subsequently the actual production process. In unfavourable cases, production from an oil layer could convert entirely in this way to water or gas output. Water and gas coning could thereby be a mechanism which halts uncontrolled oil flow during a blowout.

C HISTORY, CURRENT REGULATIONS AND PRACTICE

C.1. History

The Norwegian emergency response regulations of 1992 specified that dimensioning of emergency preparedness against acute oil pollution should be based on an assessment of the environmental risk in the event of discharges.

Norsk Hydro/Scandpower began to include simple forms of environmental risk analyses in overall quantitative risk analysis (QRA) for offshore installations around 1990, and were asked by the Norwegian Pollution Control Authority (SFT – now the NEA) in 1992 to hold a technical seminar on acceptance criteria for environmental harm to be used in environmental risk analyses. Following that session, Hydro began to develop a methodology for analysing environmental risk which became known as Mira. In parallel, Statoil had developed a method for such analyses known as MRA /5/.

It eventually became clear that both the Mira and the MRA solutions had differing good and less good aspects. Through a Norwegian Oil and Gas (then OLF) project, these methods were further developed to establish a common methodological approach to such analyses, also known as Mira /4/.

Even with this common methodology, practice differs with describing the course of events from the loss of well control until the oil reaches the sea, and for managing the related uncertainty. That includes such elements as blowout rates, durations and volumes released. See C.3.

C.2. Key provisions in current regulations

Requirements for emergency preparedness (section 40, Pollution Control Act)
“Anyone operating an enterprise which may lead to acute pollution shall provide for the necessary emergency preparedness to prevent, discover, stop, remove and limit the effect of the pollution. The emergency preparedness shall be in reasonable proportion to the probability of acute pollution occurring and to the scope of damages and disamenities which may occur.”

Risk analyses and emergency preparedness assessments (section 17, management regulations)
“The responsible party shall carry out risk analyses that provide a balanced and most comprehensive possible picture of the risk associated with the activities. The analyses shall be appropriate as regards providing support for decisions related to the upcoming processes, operations or phases. Risk analyses shall be carried out to identify and assess what can contribute to, i.a., major accident risk and environmental risk associated with acute pollution, as well as ascertain the effects various processes, operations and modifications will have on major accident and environmental risk.

“Necessary assessments shall be carried out of sensitivity and uncertainty.

“The risk analyses shall

a) identify hazard and accident situations,
b) identify initiating incidents and ascertain the causes of such incidents,
c) analyse accident sequences and potential consequences, and
d) identify and analyse risk-reducing measures, cf. Section 11 of the Framework Regulations and Sections 4 and 5 of these regulations.

“Risk analyses shall be carried out and form part of the basis for making decisions when e.g.:
a) identifying the need for and function of necessary barriers, cf. Sections 4 and 5,
b) identifying specific performance requirements of barrier functions and barrier elements, including which accident loads are to be used as a basis for designing and operating the installation/facility, systems and/or equipment, cf. Section 5,
c) designing and positioning areas, cf. Section 5 of the Facilities Regulations,
d) classifying systems and equipment, cf. Section 46 of the Activities Regulations,
e) demonstrating that the main safety functions are safeguarded,
f) stipulating operational conditions and restrictions,
g) selecting defined hazard and accident situations.

“For larger discharges of oil or condensate, simulations of drift and dispersion shall be carried out.

“Emergency preparedness analyses shall be carried out and be part of the basis for making decisions when e.g.

a) defining hazard and accident situations,
b) stipulating performance requirements for the emergency preparedness,
c) selecting and dimensioning emergency preparedness measures.

“The environmental risk and emergency preparedness analyses shall be updated in case of significant changes affecting the environmental risk or the emergency preparedness situation. In any case, updating needs shall be assessed every five years. The assessment shall be documented and made available to the Norwegian Environment Agency on request.”

Risk reduction principles (section 11, framework regulations)
“Harm or danger of harm to people, the environment or material assets shall be prevented or limited in accordance with the health, safety and environment legislation, including internal requirements and acceptance criteria ... In addition, the risk shall be further reduced to the extent possible ... Assessments as mentioned in this section, shall be carried out during all phases of the petroleum activities.”

Establishment of emergency preparedness (section 73, activities regulations)
“The operator or the party responsible for operating a facility shall prepare a strategy for emergency preparedness against hazard and accident situations, cf. also Section 9 litera c. The emergency preparedness shall be established, inter alia, on the basis of results from risk and emergency preparedness analyses as mentioned in Section 17 of the Management Regulations and the defined hazard and accident situations and barrier performance requirements, cf. Section 5 of the Management Regulations.

"The emergency preparedness against acute pollution shall cover the ocean, coast and shoreline. The operator shall have three independent barriers, cf. Section 5 of the Management Regulations, one near the source, one in fjord and coastal waters and one at shoreline. The barrier near the source and in the open sea shall be able to handle the quantity of pollution that can fall to the barrier. Barriers in fjord and coastal waters and at shoreline shall be able to handle the quantity of pollution that can fall to the barrier after the effect of the previous barrier has been taken into account.

"Where the emergency preparedness is related to activities as mentioned in Section 25 of the Management Regulations, Section 26 of the Management Regulations applies.

"The Norwegian Environment Agency can set more detailed requirements for the extent of this emergency preparedness."

C.3. Current practice

The practice most commonly observed among the oil companies when calculating blowout rates seems to be the following.

1. A number of blowout scenarios, collectively considered to provide a sufficiently representative picture, are defined.
2. Conditional probabilities for these scenarios are established.
3. Flow rates are calculated for each scenario.
4. A more or less refined probability distribution for rates is determined on the basis of calculated scenario rates and the associated probabilities.
5. A value from the upper half of the distribution is used in the environmental risk analysis.

Between one and five scenarios are typically chosen, depending on the type of operation, well and reservoir complexity, and well location.

In most cases, statistics from /10/ and /11/ provide an important part of the basis for determining probabilities with the selected scenarios.

Flow rates are calculated in collaboration with internal drilling and well experts at the companies or with external consultants.

Practice with handling uncertainty in steps 1-5 above varies greatly. One aspect is the degree of conservatism, which varies between

- extensive use of expected values
- use of conservative values for some quantities in the calculations and more neutral values for others
- use of fairly strong conservative values at all stages.

Another aspect is how uncertainty is described in the resulting expression for the blowout rate. Practice varies between the use of continuous distributions, discrete distributions and deterministic values. In the last of these categories, some of the companies operate with concepts such as Q_{max} and Q_{dim}. The interpretation of these concepts varies.

Both statistics and expert assessments are used as the basis for determining probability distributions. The weight given to these two information sources varies between the companies.

When calculating blowout duration, most people utilise the methodology described in /10/. Duration assessments are often simplified by concentrating attention primarily on drilling a relief well as the cessation mechanism. This simplification is regarded as conservative.

The procedure most commonly followed involves determining values for the total volume discharged on the basis of the rate and duration assessments. Another method used is to determine a distribution for volume first and then establish rate and duration distributions on that basis.

A relatively widespread weakness with current practice is the level of argument made for chosen rate and duration calculations. Assumptions and suppositions are applied in most analyses without sufficient argument that these are reasonable for the relevant well or operation. That applies to the choice of model, simplifications, determination of probabilities and the use of statistics, which are not necessarily representative for the case in question. This often contributes to poor traceability, which can help to weaken confidence in the analyses.

D EXAMPLES OF APPLYING THE GUIDANCE

This appendix provides three examples of rate and duration calculations intended to illustrate the practical use of the guidelines. These are as follows.

1. Drilling a production well.
2. Drilling an exploration well.
3. Combining rate and duration calculations for individual operations on a field.

D.1. Example 1 – drilling a production well

D.1.1 General

This example is intended to outline a rate and duration calculation corresponding to a B level of detail in figure 3.2 for drilling a production well. For comparative purposes, a level C calculation has also been performed. The purpose is to illustrate how far conservative simplifications influence the result.

The example is based on a real well, with the well path outlined in figure D.1. The water depth is 286 metres and the well is assumed to be drilled from a mobile floating rig. Running casing and cementing have been excluded from the example.

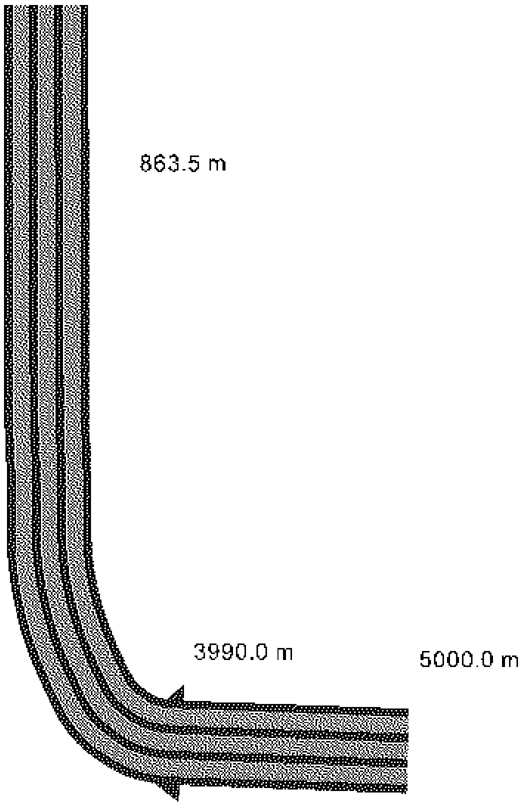

Figure D.1 Outline of the well path, with 9 5/8” casing set in a 12 ¼” hole at 3 990 metres. The 1 000-metre-long horizontal reservoir section is drilled with an 8 ½” bit.

D.1.2 Definition of blowout scenarios

Scenarios and associated probabilities are shown by figure D.2 and table D.1. A release point on the seabed is assumed for all scenarios.[11]

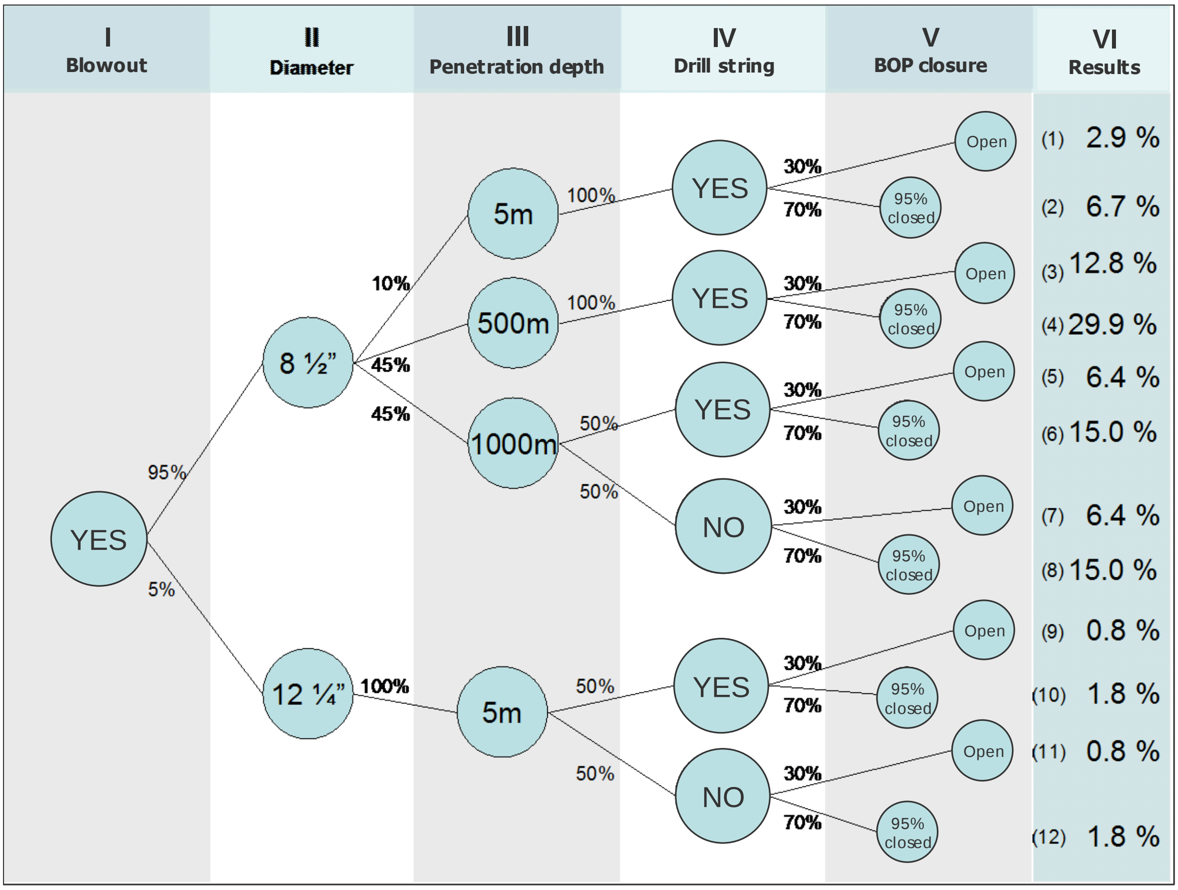

Figure D.2 Development of blowout scenarios with probabilities.

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[11] Note that the probability values and the associated justification have been made up for this example. Similar well-specific reasoning must be applied for each real-world analysis and should be documented.

Table D.1 Assessments related to the development of blowout scenarios. See figure D.2

Branch point	Assessments related to branch probabilities
I	A kick and consequent blowout are possible outcomes when drilling into the reservoir, but highly unlikely in this case since it is a production well in an area where reservoir geometry and pressure are well known. This type of incident is also likely to result, with a fair degree of probability, in a gas blowout. Five per cent is a representative figure for an exploration well, and must be considered conservative in this context.
II	The probability of a kick because of higher-than-expected pressure or unintentionally low mud pressure is set at 10 per cent for five metres of penetration. The value for exploration drilling could have been raised to 40 per cent. Ten per cent is regarded as neutral here. A kick while tripping out of a fully drilled well normally contributes about 25 per cent. Other mechanisms are distributed over other degrees of penetration. Distributing the final 90 per cent equally over the half-drilled and fully drilled reservoir sections is regarded as somewhat conservative.
III	Two cases are assumed: swabbing in and detecting a kick with the bit close to the bottom or swabbing in reservoir fluid on the way out which is not detected before the string is out of the well. While the first case clearly has the higher probability, 50-50 is assumed as a conservative simplification.
IV	Divided here between two cases: the BOP fails to close at all, or 95 per cent of the well cross-section is closed. Since the BOP represents a high-reliability system, 30 per cent for a fully open well is to be regarded as conservative. Where partial closure is concerned, 95 per cent is regarded as reasonable or somewhat conservative. Same assessment for all scenarios.
Residual	One hundred per cent means that probability has been transferred from possible but excluded outcomes with more favourable consequences.

D.1.3 Rate calculations

Rates have been calculated with the aid of the Drillbench/DynaFloDrill model from Rogaland Research (RF) /21/. Inputs are specified in table D.2. The results are given for each scenario in table D.3.

Calculations are based on the Corebook friction model, which corresponds well with a more advanced rate calculation conducted by the relevant project itself. That yielded 9 500 cubic metres per day with six-inch tubing, while a test with this model calculated 10 389m^3/d with 6” tubing.

Only the initial rate was assessed, and this was assumed to be constant over the time it takes to kill the well – in other words, no account was taken of pressure drop in the reservoir or other mechanisms which might influence the rate over time. See also figure 4.3. The effect of sand production on bottom hole pressure has been excluded.

Both these exclusions are conservative simplifications. A reduction in the oil cut in the blowout medium over the blowout course as a result of gas coning has been taken into account. See the input in the next section on duration.

The project team claims to be well informed about the reservoir parameters applied. This is not unreasonable since the well is a producer and data are available from earlier wildcat and appraisal wells. The uncertainty which was discussed would not have a significant influence on the results. A sensitivity calculation was carried out for permeability, but even substantial deviations from the specified values had little effect. Deterministic values have accordingly been applied.

Combining the results in table D.3 to obtain the probability distribution for the rate and a further combination with gas coning and the cessation mechanism results are presented in section D.1.5.

Table D.2 Input for rate calculations.

Quantity	**Value**
Water depth	286m
GOR	330
Permeability	150mD
Viscosity	0.2cP
Pore pressure	378 bar
Porosity	15%
Horizontal well length	1 000m
Drill string diameter in 12 ¼” section	6 5/8”
Drill string diameter in 8 ½” section	5”

Table D.3 Calculated rates for the 12 defined scenarios. See figure D.2

Scenario	**Probability**	**Rate (m^3/d)**
1	2.9%	1 912
2	6.7%	1 705
3	12.8%	5 011
4	29.9%	4 435
5	6.4%	5 414
6	15.0%	4 781
7	6.4%	13 248
8	15.0%	11 520
9	0.8%	2 707
10	1.8%	2 615
11	0.8%	3 283
12	1.8%	3 000

D.1.4 Duration calculations

The following cessation mechanisms have been taken into account.

1. *Blowout ceases as a result of gas coning.* Combined oil and gas flow changes to pure gas and the oil stream ceases. The probability of complete gas coning increases the closer the horizontal well section is placed to the oil-gas contact (OGC), and is higher for short open hole sections than for long ones. Based on that and on input from the project, probability distributions have been determined for three cases on the basis of the defined blowout scenarios:
2.
    a. 5m exposed reservoir, triangular distribution T(1,10,90) days, see figure D.3
    b. 500m exposed reservoir, triangular distribution T(2,21,90) days
    c. 5 000m exposed reservoir, triangular distribution T(2,45,90) days.
3. *Blowout ceases after killing with the aid of a relief well*. The process of drilling a relief well can be divided into three phases,[12] and duration distributions have been determined with the aid of a well control expert.

    a. Mobilisation and positioning of the rig. Two possibilities exist here – either using the original rig for the first stage of drilling the relief well, or waiting until a new unit arrives. The probabilities of using the existing rig or waiting are set at 90 and 10 per cent respectively. Time to mobilisation and positioning is represented in both cases by triangular distributions: T(2,3,4) days and T(10,12,14) days respectively.
    b. Drilling down to the immediate vicinity of the bottom of the blowing well. This contribution to time is represented by the triangular distribution T(20,25,30) days.
    c. Drilling into the blowing well and killing it. This contribution to time is represented by a stepped linear distribution SL(0,0.5,2,5,30) days. See figure D.5.[13]

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[12] Note that a smaller mesh size, divided into more than three phases, is also commonly used.

[13] Note that all these distributions are invented examples and should not be used directly in real-world analyses.

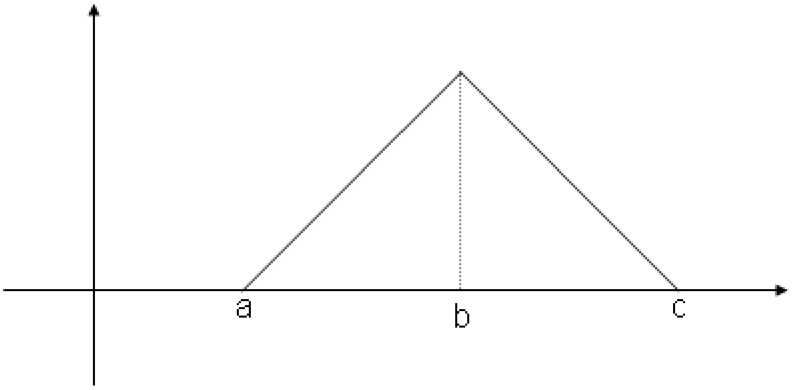

Figure D.4 Triangular distribution T(a,b,c). The distribution does not necessarily have the symmetry shown in the figure.

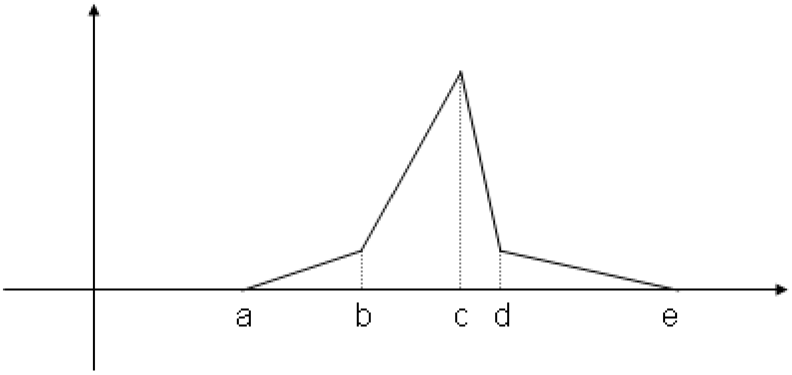

Figure D.4 SL(a,b,c,d,e) is a five-point stepped linear distribution which starts from a (zero percentile) and has the 10th percentile at b, its peak at c, the 90th percentile at d and its termination at e (100th percentile).

The *natural cessation* and *bridging* main mechanisms, see sections B.4 and B.2 respectively, have been excluded. Natural cessation as a result of pressure reduction is regarded as irrelevant for this well. Nor has information been received which indicates that natural cessation because of global collapse will make a contribution, given the input taken into account for these two mechanisms. Bridging as a result of sand production is considered unlikely – the high flow rates will clean sand from the well. The accumulation of large fragments flaking from the well wall has not been assessed. Excluding this mechanism is regarded as a conservative simplification.

D.1.5 Results

The principal results are presented through the diagrams below.

Figure D.5 presents a combined rate and duration plot corresponding to figure 4.2.

Figure D.6 presents a combined rate and duration plot on the assumption that gas coning is the only cessation mechanism and drilling of a relief well is ignored.

Figure D.7 presents a combined rate and duration plot on the assumption that drilling of a relief well is the only cessation mechanism and gas coning is ignored.

Figure D.8 presents the distribution for blowout duration viewed in isolation.

Figure D.9 presents the distribution for blowout rate viewed in isolation.

Figure D.10 presents the distribution over the total volume discharged.

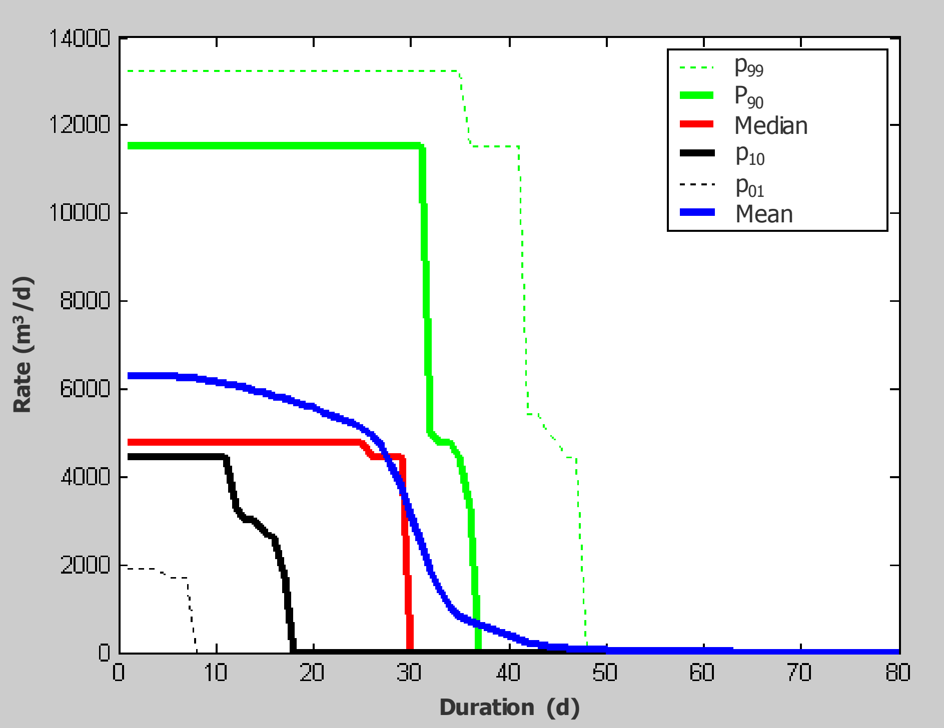

Figure D.5 Rate and duration when both cessation mechanisms are taken into account.

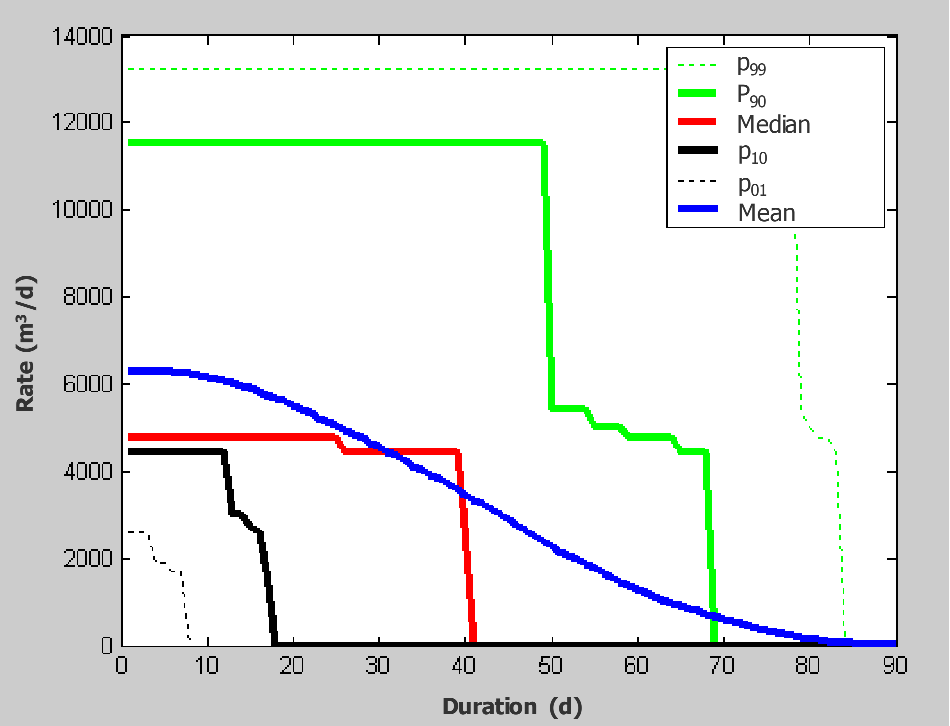

Figure D.6 Rate and duration when gas coning is the only cessation mechanism.

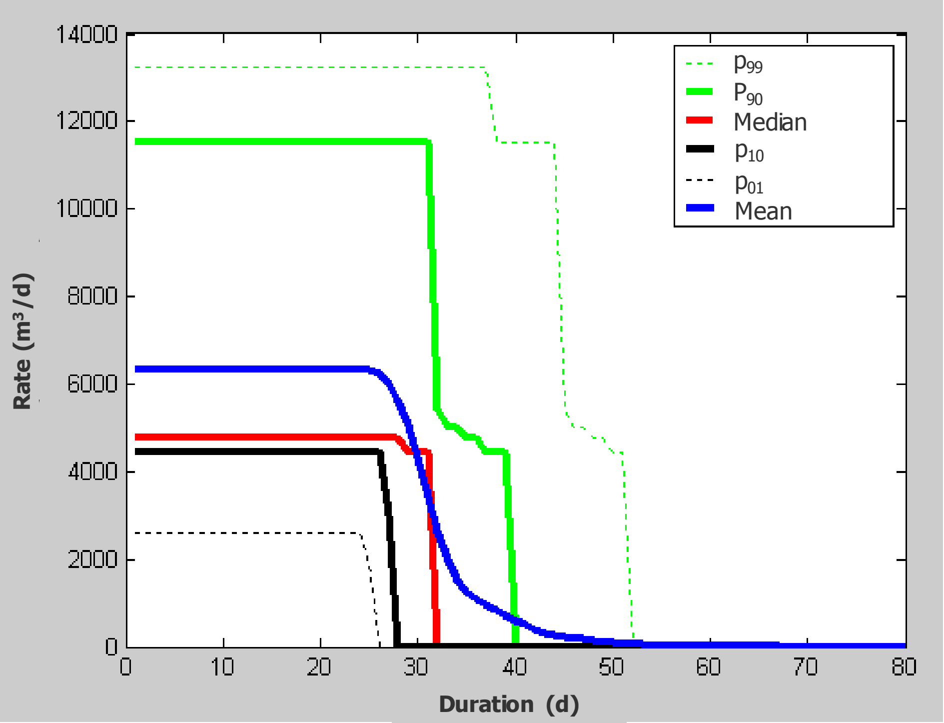

Figure D.7 Rate and duration when drilling a relief well is the only cessation mechanism.

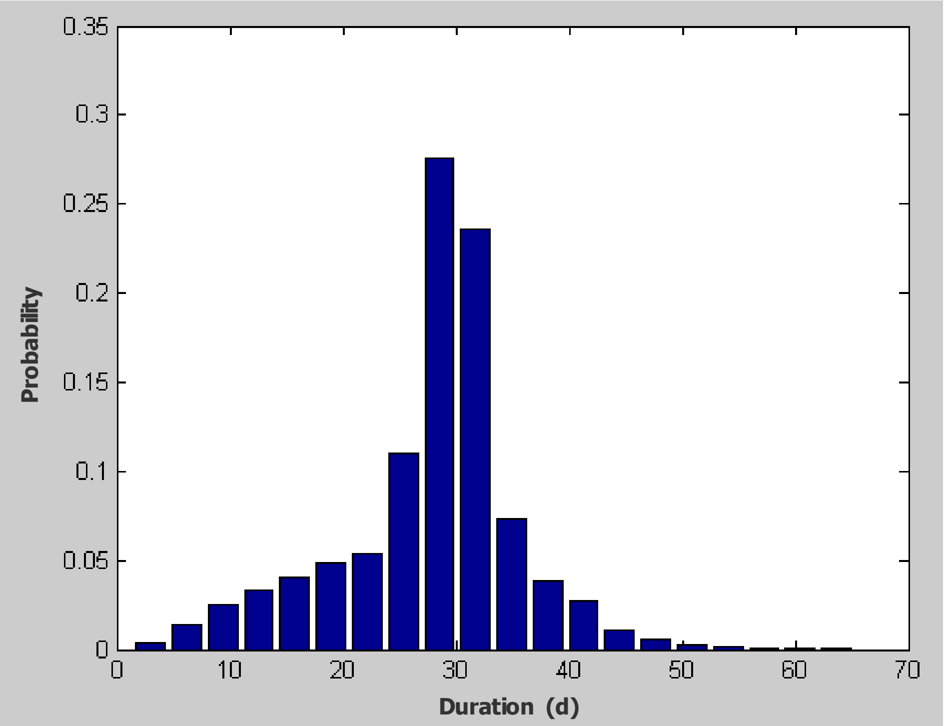

Figure D.8 Marginal distribution for blowout duration.

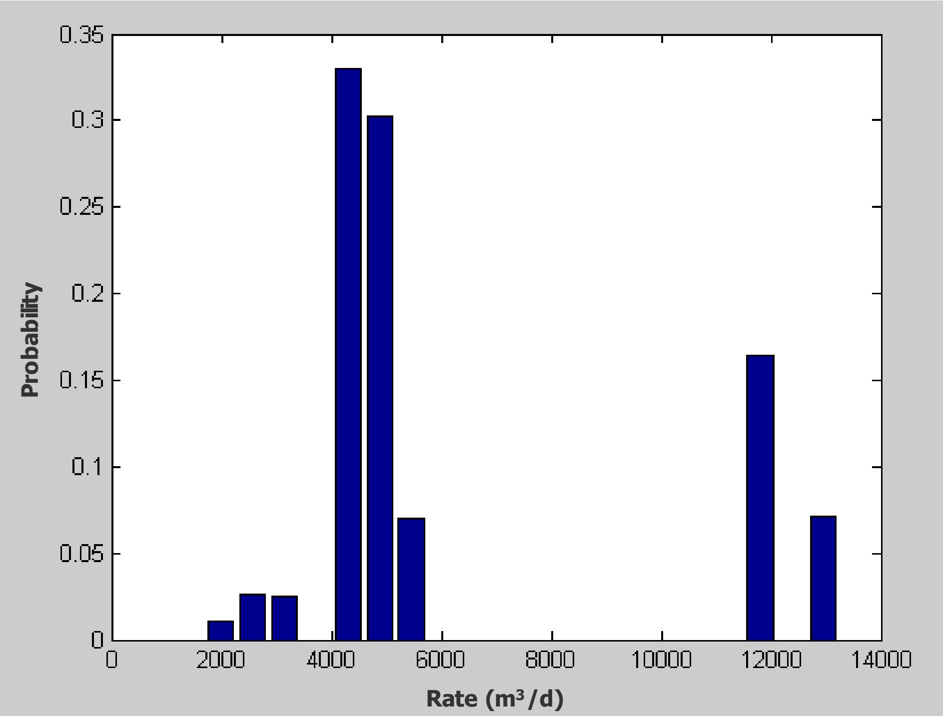

Figure D.9 Marginal distribution for initial blowout rate.

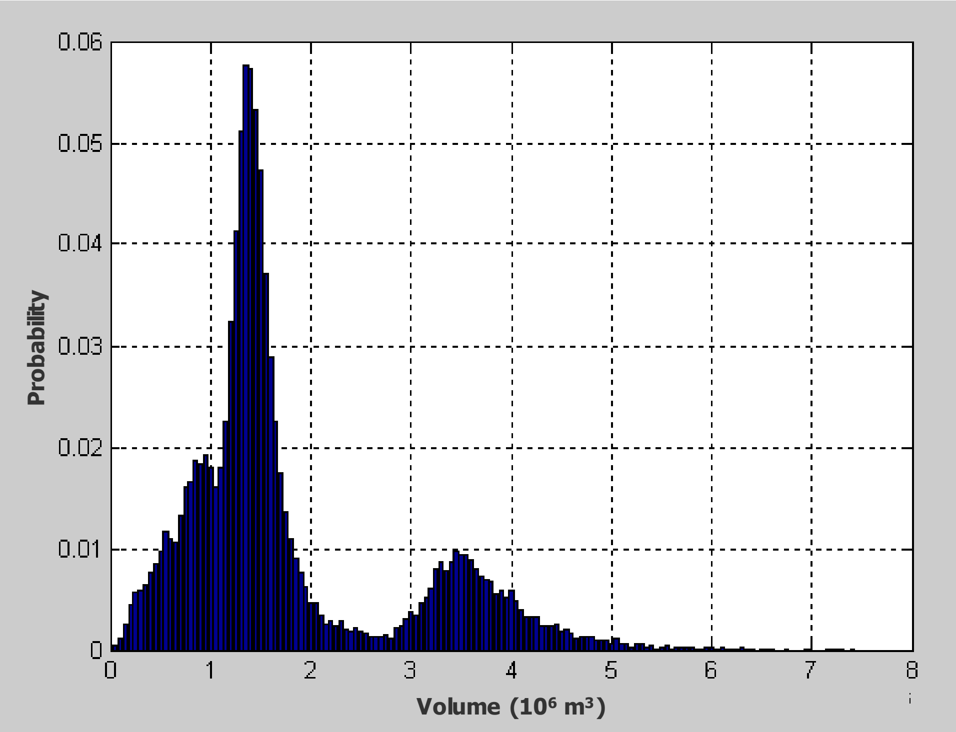

Figure D.10 Distribution over the discharged volume.

D.1.6 Additional assessment at C level of detail

The calculations so far have been at the B level of detail, as outlined at the beginning of this chapter. What are the consequences of using simplified, more conservative calculations at level C? As described in chapter 5, the 90th percentile for the various quantities may then be used as input to the calculations.

The primary source of uncertainty for blowout rates in this example is the blowout scenario. The most unfavourable of these is number 7, with a rate of 13 248m^3/d. See table D.3. However, this has a probability of 6.4 per cent and is therefore arguably conservative since it lies outside the 90th percentile. The next most unfavourable scenario is number 8, with a rate of 11 520m^3/d and a probability of 15 per cent. The 90th percentile arguably lies here.

Where duration is concerned, the effect of gas coning as a cessation mechanism would be ignored at level C and attention concentrated on drilling a relief well. As shown in section D.1.3, the process of drilling a relief well is modelled as three successive operational phases. Summing the 90th percentiles in the distributions determined for execution times for these phases gives a duration of 36.6 days.

Multiplying calculated rate and duration gives a total of 422 632m^3 in volume discharged. Selecting the 90th percentile from the volume calculations at level B in figure D.10 provides an approximate figure of 364 000m^3. In this case, therefore, an approach at the C level of detail yields a 16 per cent volume reduction. This is a moderate difference, but the limited degree of uncertainty in this example must be borne in mind.

D.2. Example 2 – drilling an exploration well

D.2.1 General

This example concerns an exploration well and repeats the calculations performed with the first example in section D.1 for a production well. Note that sub-surface conditions for the two wells have a number of features in common but that, since this is an exploration well, the degree of uncertainty associated with these is now substantially greater. Also note that this well is vertical and planned with a far smaller area exposed to the reservoir. The purpose of the example is to convey how different degrees of uncertainty about conditions in the formation affect calculations and results. The analysis is conducted with the same level of detail as example 1 – in other words, within level B in figure 3.2. Finally, a supplementary calculation is again performed at level C in order to illustrate how more simplified and conservative figures affect the results.

The example is based on a real well being planned. Pressure conditions versus depth and the setting depth for casing are outlined in figure D.11. The water depth is 273 metres. A mobile floating rig is assumed to drill the well.

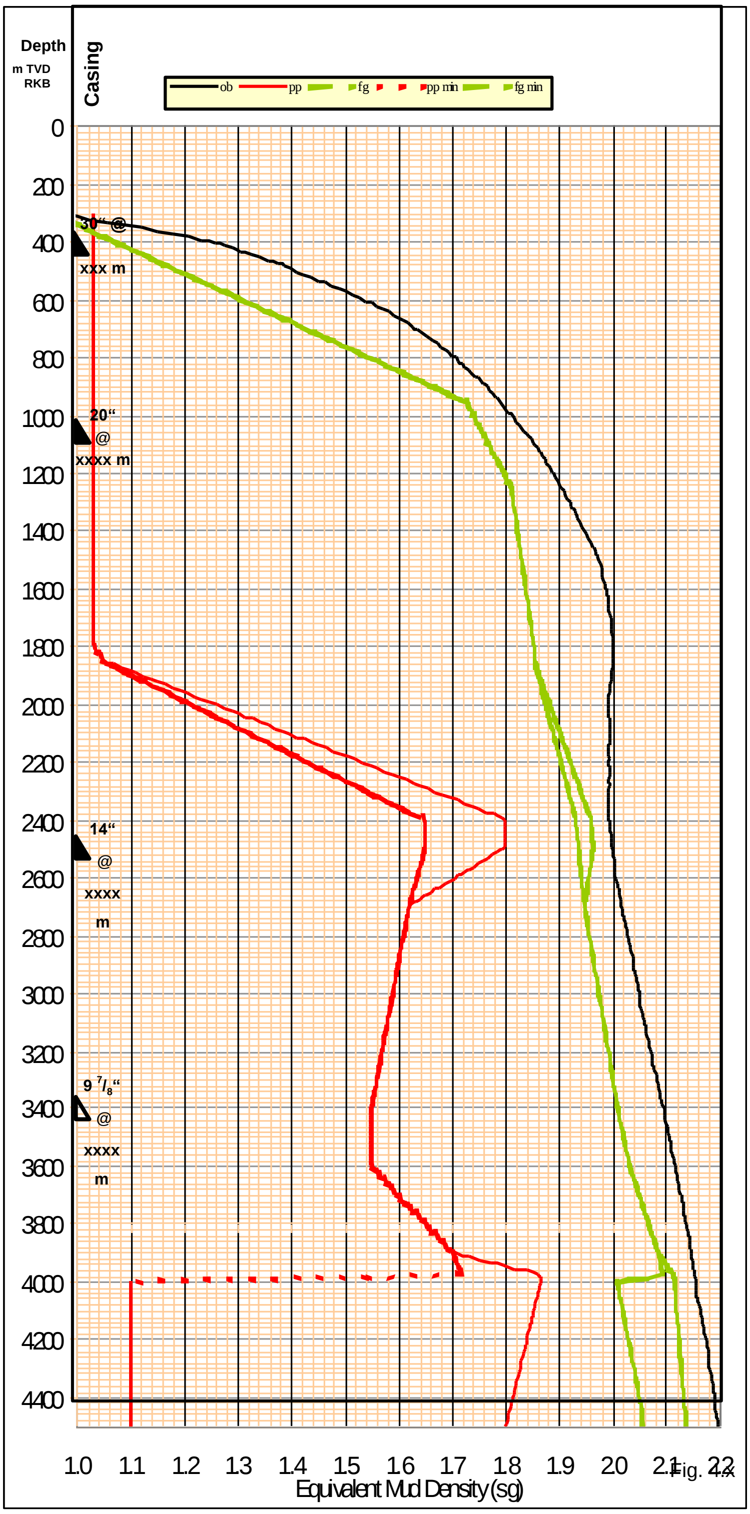

Figure D.11 Plot of the pore pressure (red), fracturing pressure (green) and overburden pressure (black) gradients against depth, as well as the planned setting depth for casing in a planned exploration well. Note the great uncertainty over the pore pressure in the reservoir from about 4 000m and down.

D.2.2 Definition of blowout scenarios

Scenarios and associated probabilities are presented in figure D.12 and table D.4. A release point at the seabed is assumed for all scenarios.[14]

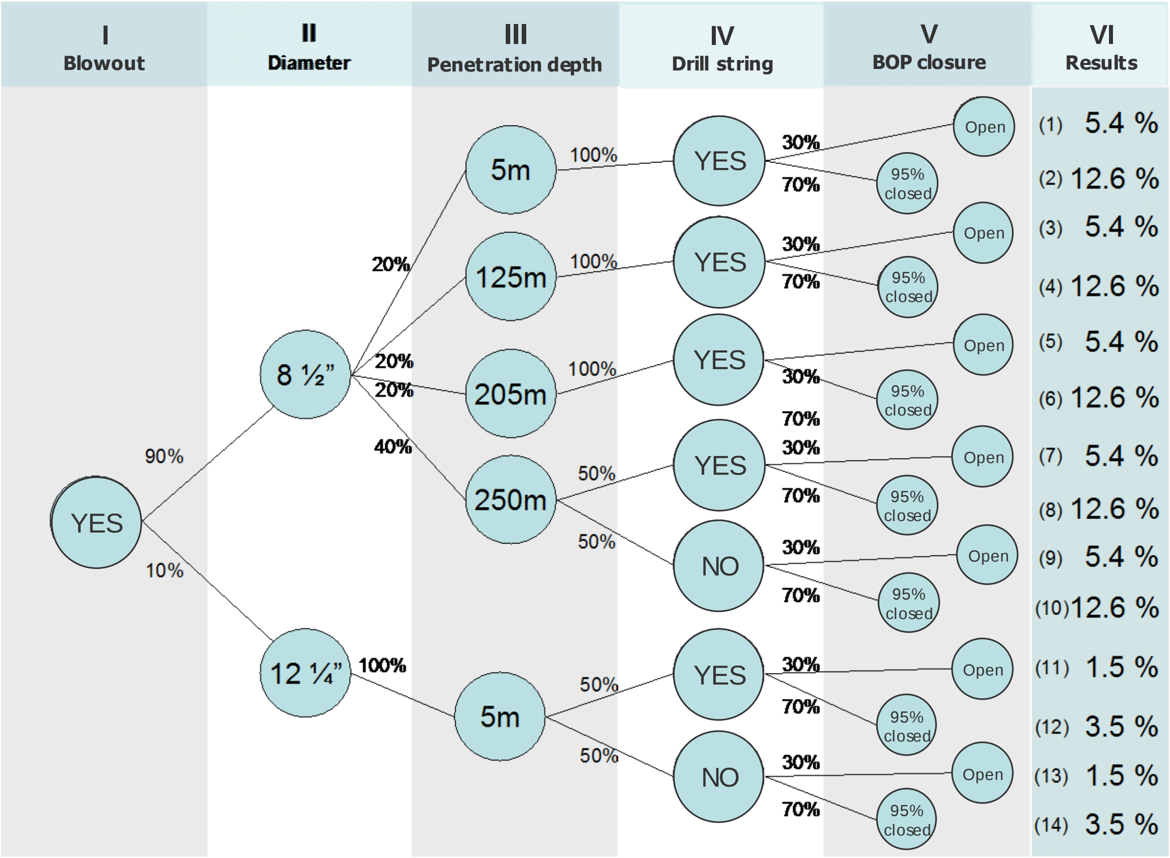

Figure D.12 Development of blowout scenarios with probabilities[14].

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[14] Note that the probability values and the associated justification have been made up for this example. Similar well-specific assessments must be made for each real-world analysis and should be documented. Supplementary guidance on steps II-V are found in the guideline amendment /1/.

Table D.4 Assessments related to the development of blowout scenarios. See figure D.12.

Branch point	Assessments related to branch probabilities
I	A kick when drilling into the reservoir and a subsequent blowout are more probable in this exploration case than with production drilling. See table D.1. The degree of uncertainty related to reservoir geometry is greater in an exploration well. Once again, an incident of this kind will have a certain probability of resulting in a gas blowout. The specified probability of 10 per cent is regarded as somewhat conservative.
II	The probability that a blowout will be caused by a kick when drilling (five metres) into each new reservoir zone is judged to be 20 per cent. The kick mechanism is either higher-than-expected pore pressure or unintentionally low mud pressure. These relatively high probabilities are set with an eye to the relatively high level of uncertainty over pore pressure in exploration wells. A kick when tripping out of a fully drilled well normally contributes about 25 per cent. Other mechanisms should be distributed over all degrees of penetration, but are allocated here to tripping at full penetration – a conservative simplification – which gives this a probability of 40 per cent.
III	Two cases are assumed: swabbing in and detecting a kick with the bit close to the bottom or swabbing in reservoir fluid on the way out which is not detected before the string has left the well. While the first case clearly has the higher probability, 50-50 is assumed as a conservative simplification.
IV	Divided here between two cases: the BOP fails to close at all, or 95 per cent of the well cross-section is closed. Since the BOP represents a high-reliability system, 30 per cent for a fully open well is to be regarded as conservative. Where partial closure is concerned, 95 per cent is regarded as reasonable or somewhat conservative. Same assessment for all scenarios.
Residual	One hundred per cent means that probability has been transferred from possible but excluded outcomes with more favourable consequences.

D.2.3 Rate calculations

Rates have been calculated with the aid of the same tool used in example 1. Table D.5 shows that a larger proportion of the input values are uncertain and have thereby been described with the aid of probability distributions. The results are provided below for each scenario in table D.6, which presents minimum and maximum values for the distributions.

Only the initial rate was assessed, and was assumed to be constant over the time it takes to kill the well – in other words, no account was taken of pressure drop in the reservoir or other mechanisms which can affect the rate over time. See also figure 3.3. As with example 1, the effect of sand production on bottom hole pressure was excluded. Both these are conservative simplifications. Because significantly less was known about the reservoir in this case, no account was taken of the possibility that gas or water coning could reduce the oil cut in the blowout medium for part of the blowout course.

Combining the results in table D.5 to obtain a probability distribution for rate and with gas coning and the cessation mechanisms is presented in section D.2.5.

Table D.2 Input for rate calculations.[15]

Quantity	**Value**
Water depth (m)	273 + 23.5
Total vertical depth to top of reservoir (m)	T(3 930,3 980,4 030)
Length, 12 ¼" section (m)	1 000
Length, 8 ½" section (m)	650
Length, exposed reservoir, 12 ¼" section (m)	5
Length, exposed reservoir, 8 ½" section (m)	Three zones: 120 + 80 + 50 = 250
Pore pressure (sg)	T(1.1, 1.49,1.87)
Porosity (%)	Two formations equally likely: T(12,14,16) and T(13,17,21)
GOR	T(160,200,240)
Water cut	0
Permeability (mD)	Two formations equally likely: T(1,150,300) and T(1,50,100)
Viscosity (cP)	T(0.3,0.45,0.6)
Drill string diameter, 12 ¼" section	5 7/8"
Drill string diameter, 8 ½" section	5"
Casing diameter, 12 ¼" section	14"
Liner diameter, 12 ¼" section	9 5/8"

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[15] Note that the probability distributions are invented examples, and are not to be used directly in real-world analyses.

Table D.3 Calculated rates for the 14 defined scenarios. See figure D.12, minimum and maximum values.

Scenario	**Probability**	**Rate (m^3/d)**
1	5.4%	668-8 640
2	12.6%	334-7 373
3	5.4%	8 905-26 726
4	12.6%	6 221-24 492
5	5.4%	10 783-27 498
6	12.6%	8 329-25 344
7	5.4%	11 428-27 567
8	12.6%	8 836-25 574
9	5.4%	20 736-69 638
10	12.6%	14 642-57 946
11	1.5%	645-10 633
12	3.5%	645-7 718
13	1.5%	645-10 829
14	3.5%	645-7 258

D.2.4 Duration calculations

Only the “blowout ceases after killing with the aid of a relief well” mechanism was taken into account. Input corresponding to example 1 formed the basis.

D.2.5 Results

The principal results are presented through the diagrams below.

Figure D.13 shows the combined rate and duration plot corresponding to figure 4.2. Figure D.14 presents the distribution for blowout duration in isolation, while figure D.15 shows the corresponding distribution for the blowout rate. Figure D.16 presents the distribution over the total volume discharged.

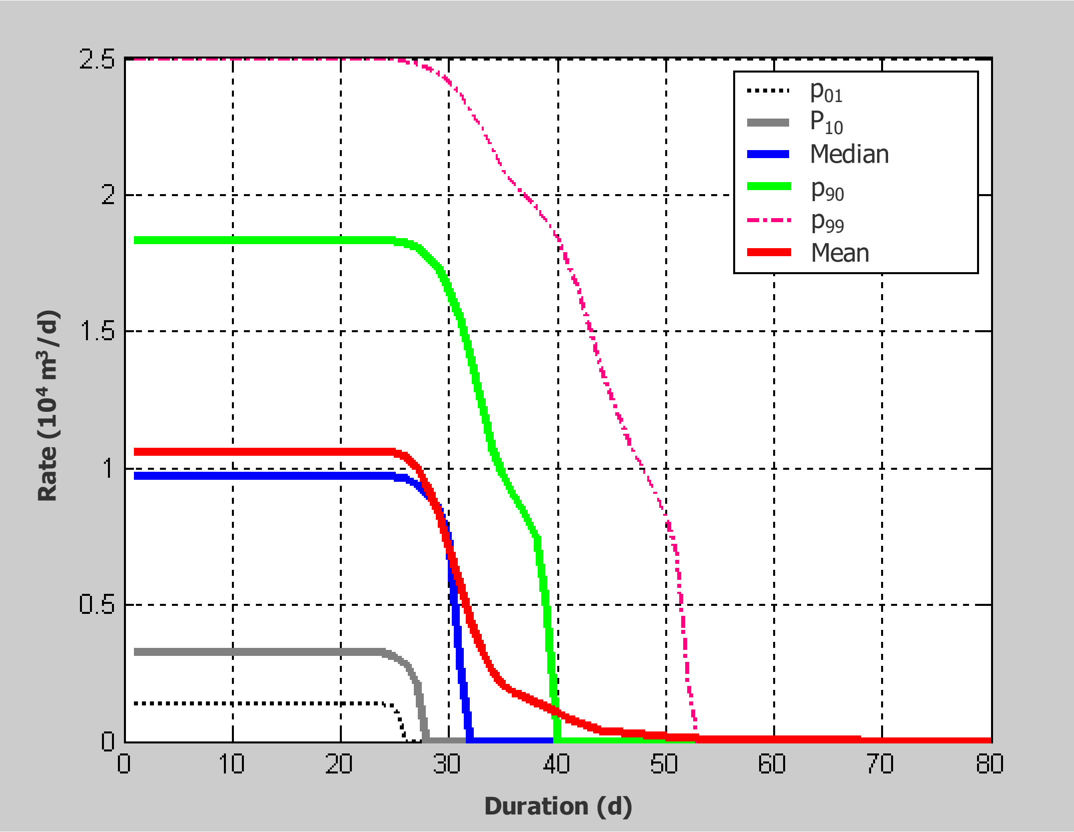

Figure D.13 Rate and duration.

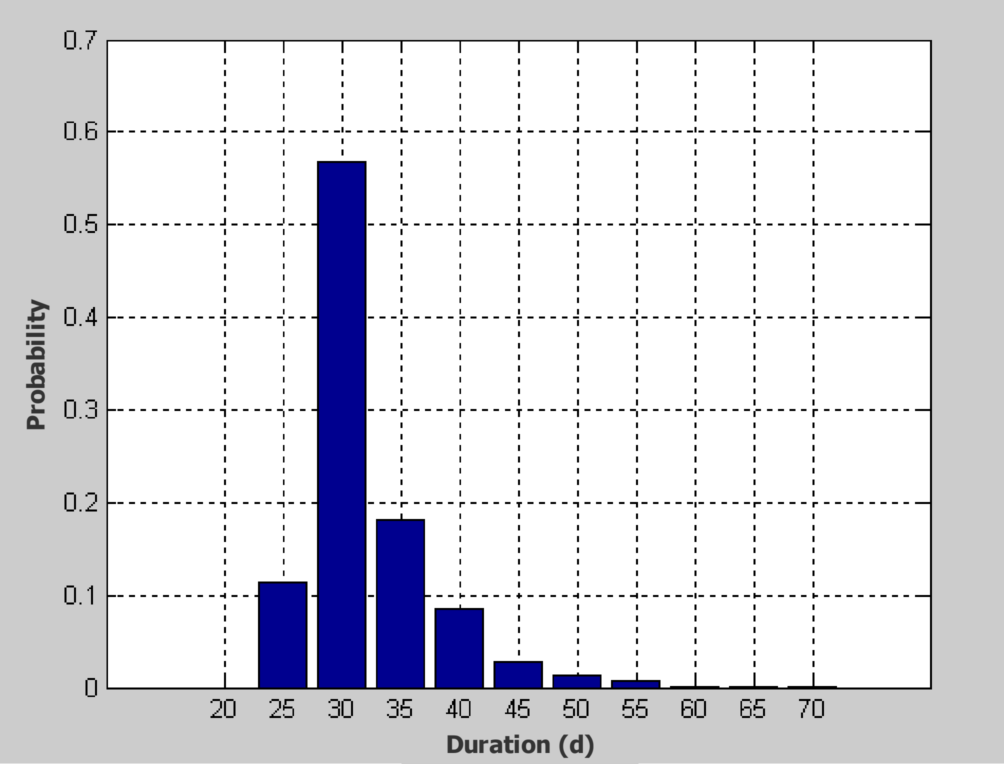

Figure D.14 Marginal distribution for blowout duration.

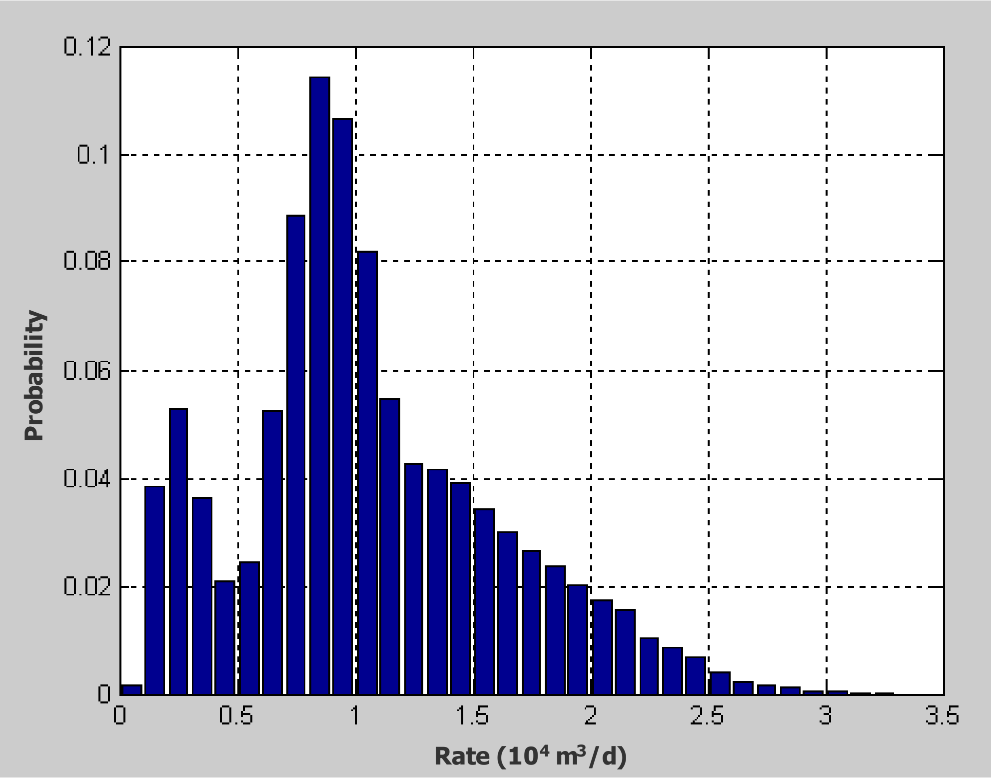

Figure D.15 Marginal distribution for initial blowout rate.

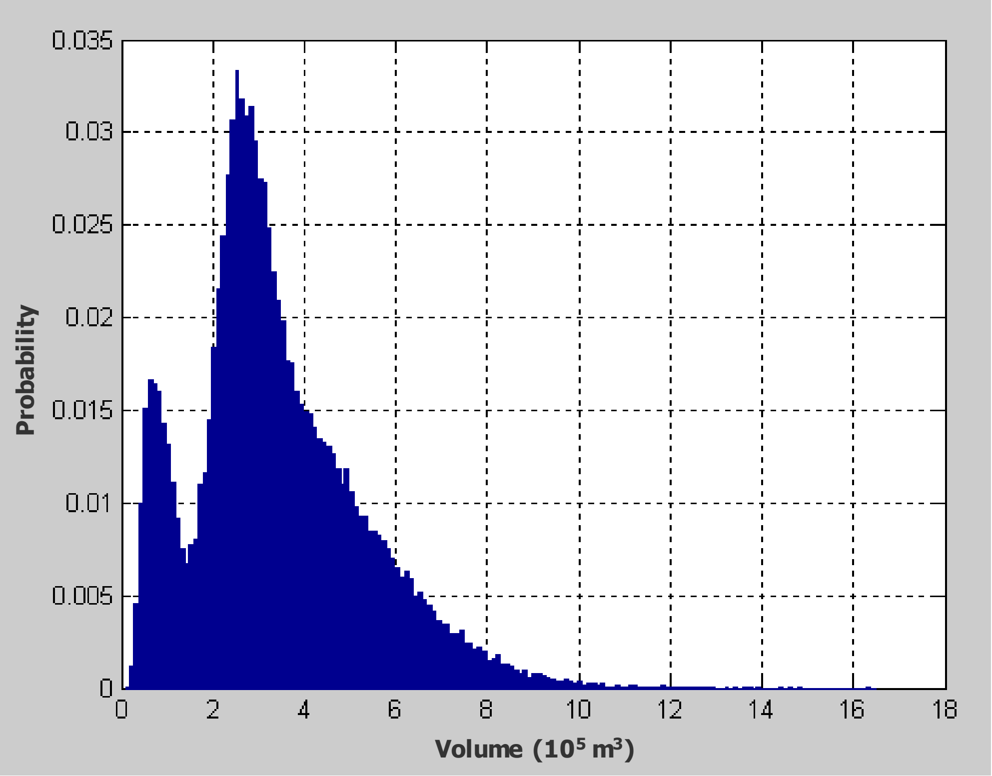

Figure D.16 Distribution over total volume discharged

D.2.6 Additional assessment at C level of detail

In example 1, reducing the level of detail in the calculations from B to C increased the total volume discharged by 16 per cent. What is the consequence in this example, where the degree of uncertainty is considerably larger?

Calculating the blowout rate on the basis of the 90th percentile in the distributions used as input for the rate calculations – see D.2.2 and D.2.3 – gives <u>28 397m^3/d</u>.

Where duration is concerned, the same approach has been chosen as in example 1. See section D.1.6. This gives a duration of <u>36.6 days</u>.

Multiplying rate and duration produces a total volume discharged of <u>1 039 330m^3</u>. Excluding the 90th percentile from the volume calculations at level B in figure D.10 gives approximately <u>597 000m^3</u>. In other words, an approach at the C level of detail yields 74 per cent in this case. Compared with the corresponding assessment in example 1, a greater degree of uncertainty over conditions which affect blowout duration and rate substantially increases the disadvantage of using a simplified, conservative approach.

D.3. Example 3 – accumulating rate and duration calculations from single operations to field level

D.3.1 General

The purpose of this example is to illustrate how rate and duration distributions calculated for a single operation, as shown in examples 1 and 2, can be accumulated:

- for operations conducted in one well over a given period
- for several wells on a field.

The level of detail in these calculations is governed to a great extent by the level of detail in the calculations which underlies rate and duration distributions for single operations and other inputs to the example. It is assumed here that these calculations lie within level B (see figure 3.2), as in examples 1 and 2. Further treatment of these inputs in this example lies at level A – in other words, corresponding to the reference methodology. An example of how the use of more simplified calculations at level C can affect the results is provided at the end of this section.

D.3.2 Input

The field is assumed to have reservoir properties similar to those used in example 1. Other conditions in the example are hypothetical. Calculations are performed for one calendar year. The following assumptions have been made as the basis for the example.

- A total of 75 wells at 1 January where a blowout could happen.
- The wells are divided into three categories: A (15 wells), B (25 wells) and C (35 wells).

- Five new wells are drilled during the year, three in category A and two in category B. Contributions from these to the risk associated with the production phase are excluded.
- Blowout probability is calculated per well year for production and per operation for drilling, completion, intervention and workover. See table D.1.
- Seven interventions planned – two in category A, three in category B and three in category C. The same type of intervention method is assumed for all cases.
- Two workovers are planned in category C wells.
- Well category A: rate and duration distributions matched to example 1 for drilling (see figures D.5, D.8 and D.9). Designated R1 and D1.
- Well category B: rate distribution R1 and duration distribution as with the case in example 1 where no account is taken of gas coning, designated D2 (see figure D.7), for drilling.
- Well category C: new rate distribution – R2 – with reduced values determined and D2 duration distribution for drilling.
- Rate and duration distributions in each category are set as equal for drilling, completion and workover.
- Production rates are assumed to have values of about two-thirds of the worst-case evaluation for drilling and assume less uncertainty.
- Rates for intervention are set somewhat higher than production, and assume greater uncertainty.
- Duration distributions for production are set as equal to drilling.
- Duration distributions determined for intervention correspond to the distributions for drilling, but with some lower central values.

Note that determining rate and duration distributions at operation and well levels in this example is not intended to illustrate the guidance, but to show how these can be combined to obtain distributions at a higher level for well and field.

An overview of the various distributions used is provided in table D.8, figures D.17 and D.18, and the subsequent text.

Table D.7 Blowout probabilities for various operations/well categories and the resulting overall probabilities.

	Blowout probability					
Well category	Drilling	Completion	Produc-tion	Interven-tion	Workover	**Total**
A and B	1.0×10^{-4}	1.5×10^{-4}	0.7×10^{-4}	2.5×10^{-4}	4.0×10^{-4}	5.3×10^{-3}
C	0.6×10^{-4}	1.0×10^{-4}	0.6×10^{-4}	2.0×10^{-4}	3.2×10^{-4}	3.1×10^{-3}
Total	5.0×10^{-4}	7.5×10^{-4}	4.9×10^{-3}	1.6×10^{-3}	6.4×10^{-4}	8.4×10^{-2}

Table D.8 Rate and duration distributions for various operations and well categories.

Well category	**A**		**B**		**C**	
Operation	***Rate*** (m³/d)	***Duration*** (day)	***Rate*** (cu.m/d)	***Duration*** (day)	***Rate*** (m³/d)	***Duration*** (day)
Drilling	R1	D1	R1	D2	R2	D2
Completion	R1	D1	R1	D2	R2	D2
Production	R3	D1	R3	D1	R4	D1
Intervention	R5	D3	R5	D4	R6	D4
Workover	R1	D1	R1	D2	R2	D2

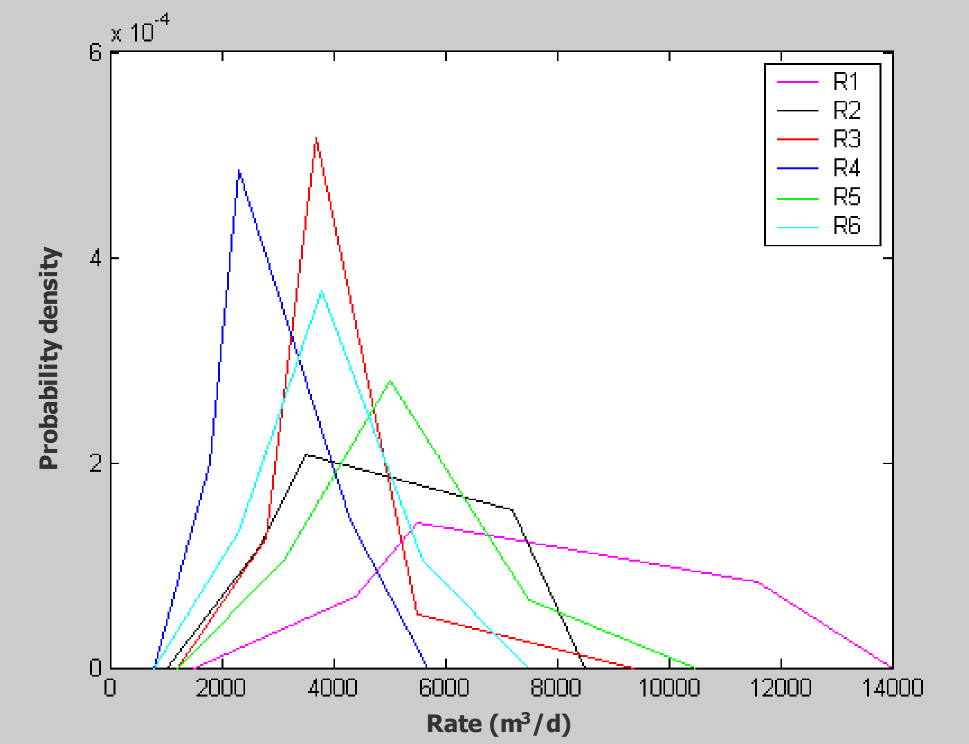

Figure D.17 Input distributions for initial blowout rate.

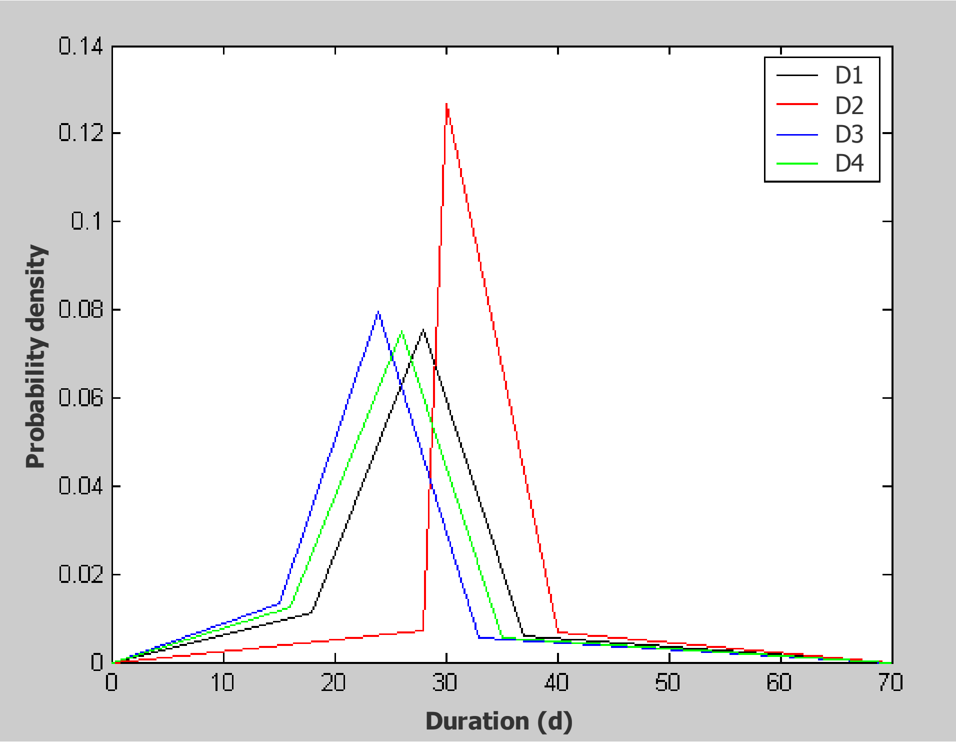

Figure D.18 Input distributions for blowout duration.

All distributions are five-point stepped linear distributions (see also figures 5.1 and D.5), given by the following.

R1: SL(1 500,4 400,5 500,11 600,14 000)
R2: SL(1 000,2 700,3 500,7 200,8 500)
R3: SL(1 200,2 800,3 700,5 500,9 400)
R4: SL(800,1 800,2 300,4 300,5 700)
R5: SL(1 200,3 100,5 000,7 500,10 500)
R6: SL(800,2 300,3 800,5 600,7 500)

D1: SL(0,18,28,37,70)
D2: SL(0,28,30,40,70)
D3: SL(0,15,24,33,70)
D4: SL(0,16,26,35,70)

D.3.3 Calculations

Monte Carlo simulations were used to calculate rate and duration distributions based on the assumptions and input values for individual operations described above, and the resulting distribution over the volume discharged. Where the course of a blowout over time and volume calculations are concerned, the rate is assumed – as in the previous examples – to be constant during the period it takes to kill the well. See also figure 4.3.

D.3.4 Results

Results which could be derived from the simulation embraced:

- total blowout probability and contribution from the various operation types and well categories – see table D.7
- overall distributions over the initial blowout rate, blowout duration and volume discharged, assuming a blowout on the field in the period – see figures D.19-D.21
- distributions over the initial blowout rate and duration, assuming a blowout in connection with a specific operation type – see figures D.22 and D.23
- distributions over the initial blowout rate and duration, assuming a blowout from a well in a specific well category – see figures D.24 and D.25.

Similarly, distributions could also be presented for various individual wells in the three categories with regard to the drilling/completion or production phases, with or without intervention and/or workover. However, the plots presented below should be sufficient for this example.

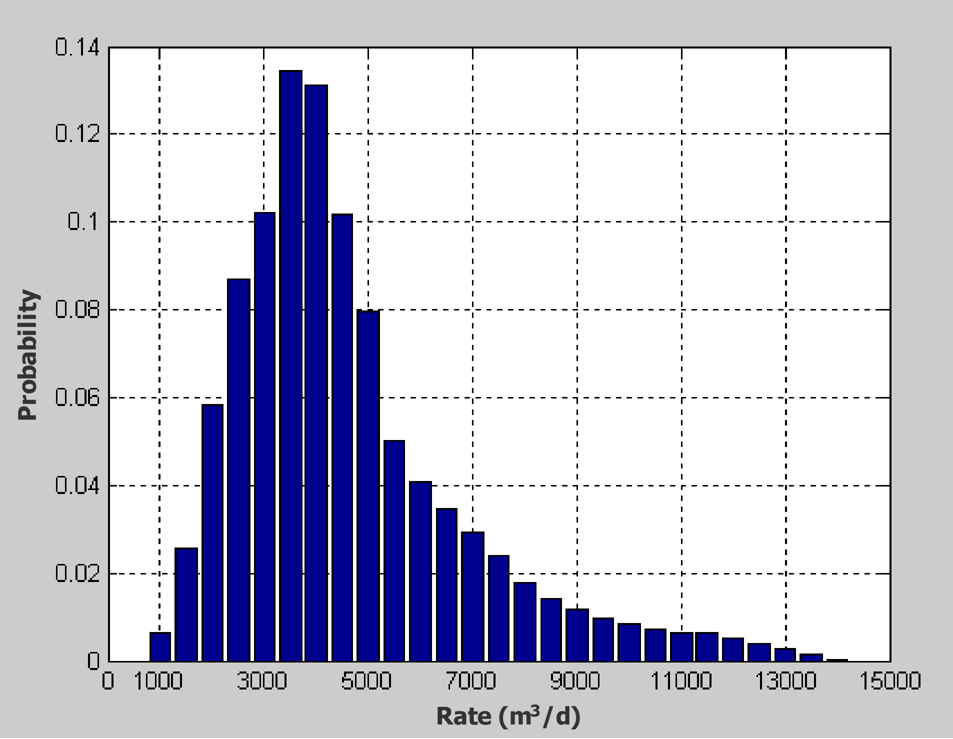

Figure D.19 Overall distribution over initial blowout rate, assuming a blowout on the field for the given calendar year.

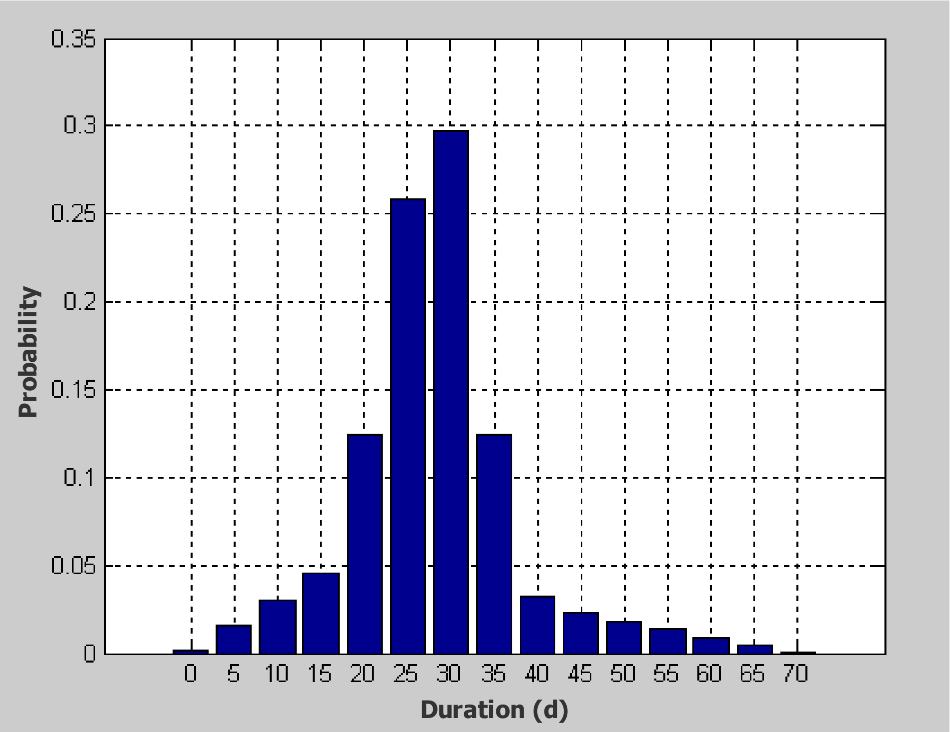

Figure D.20 Overall distribution over blowout duration, assuming a blowout on the field for the given calendar year.

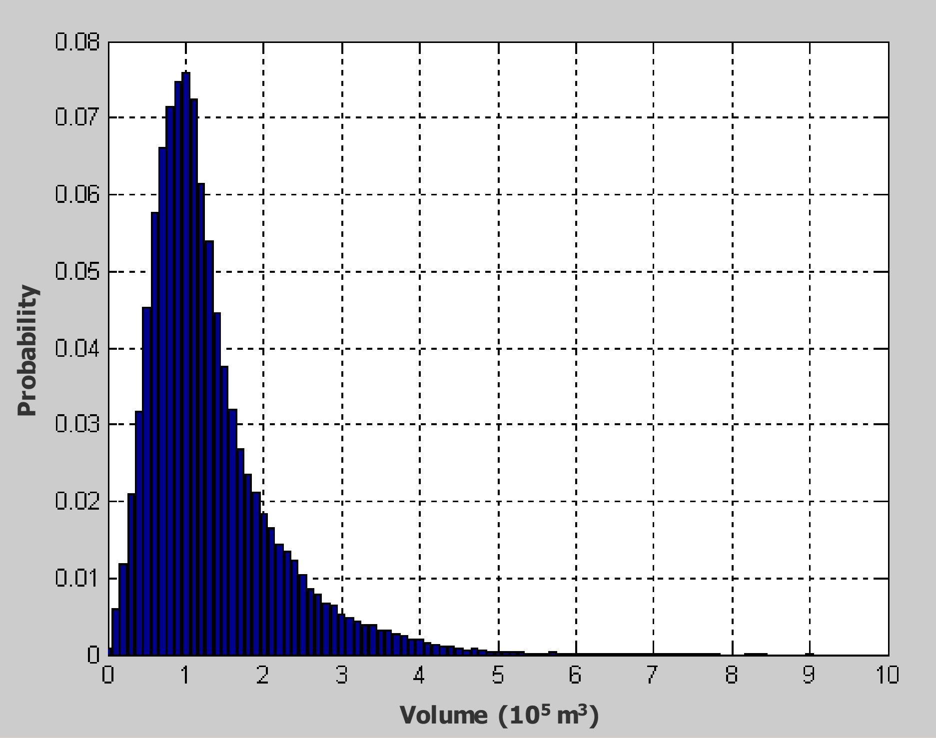

Figure D.21 Overall distribution over volume discharged, assuming a blowout on the field for the given calendar year.

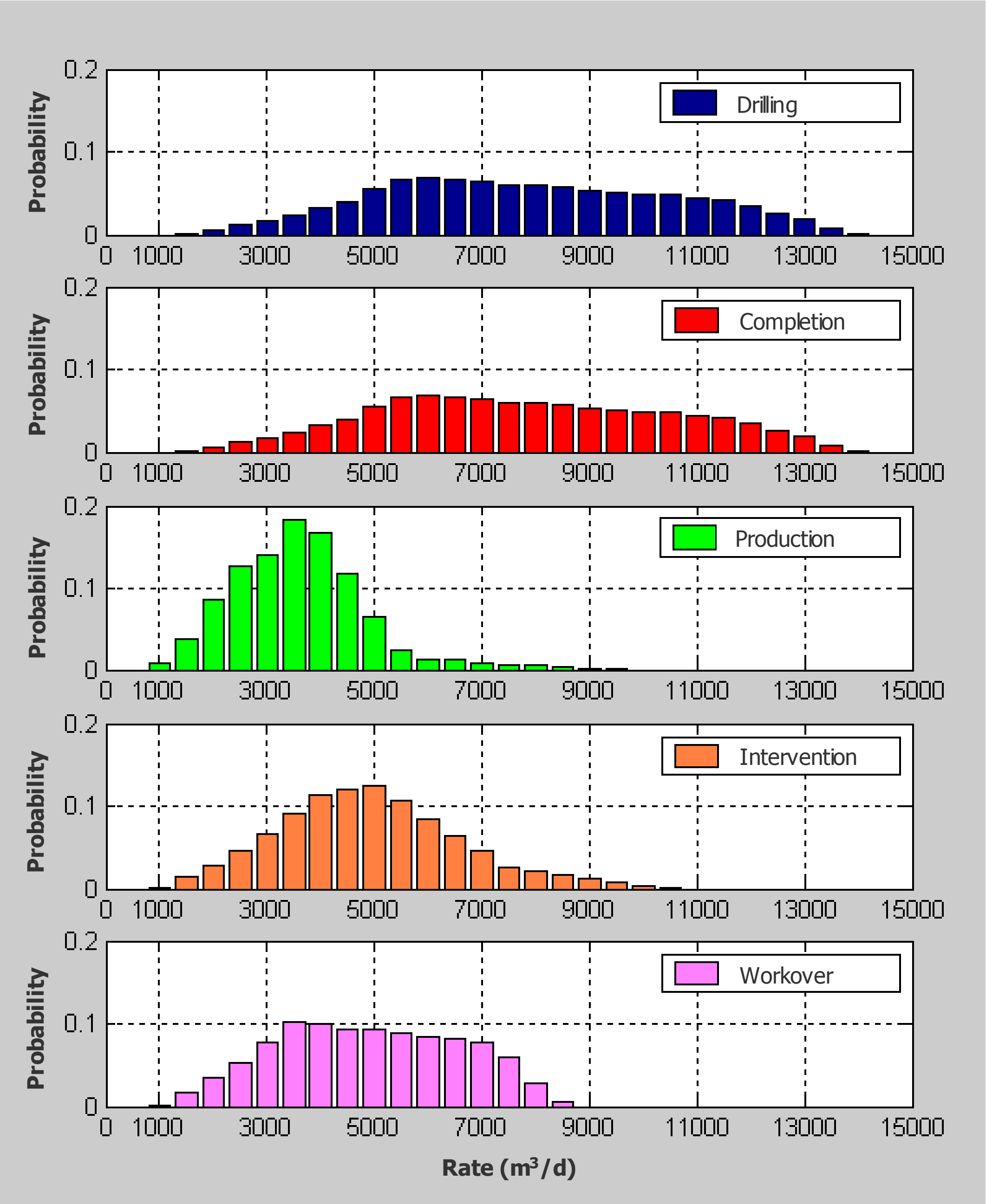

Figure D.22 Specific rate distributions for the five operation types.

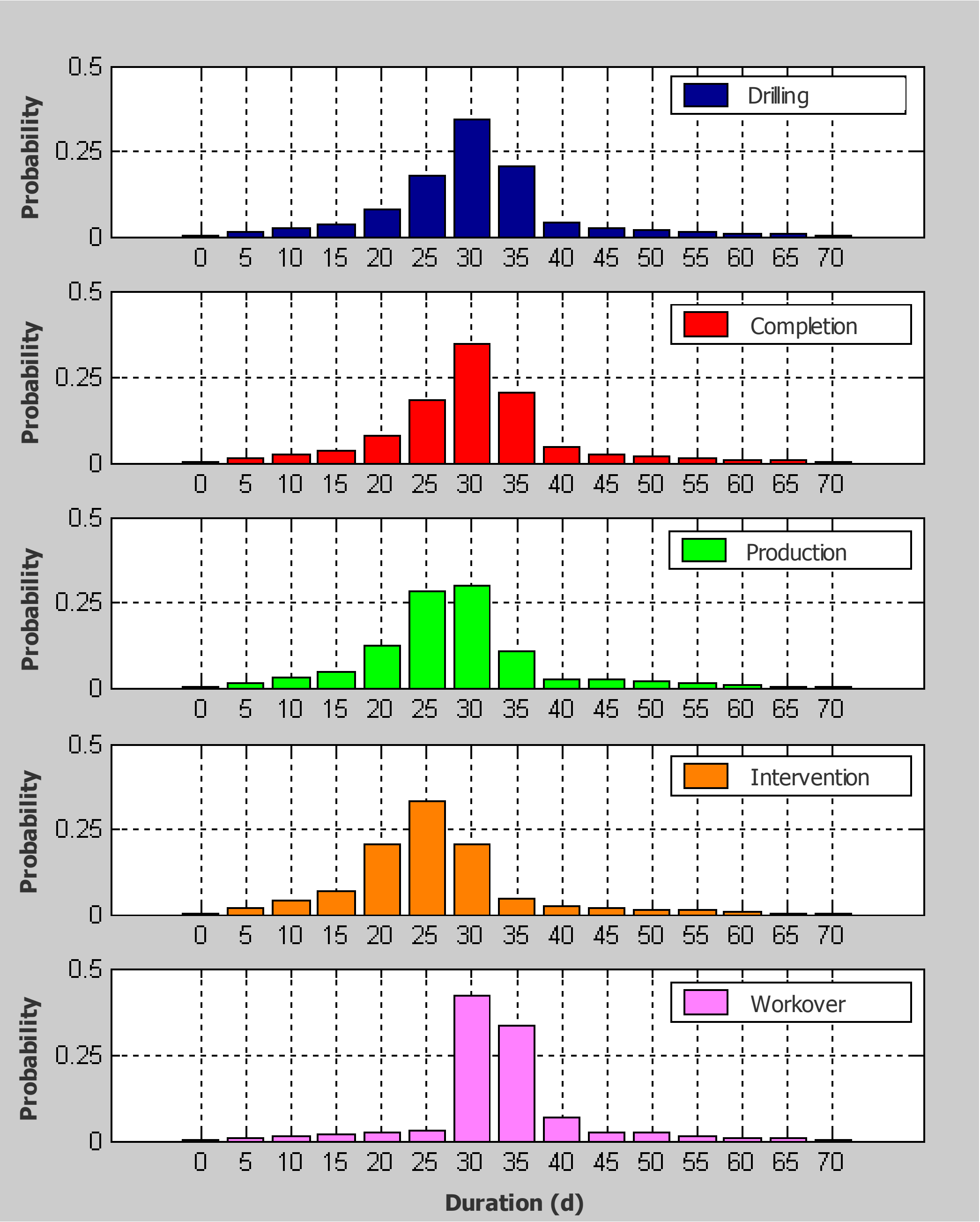

Figure D.23 Specific duration distributions for the five operation types.

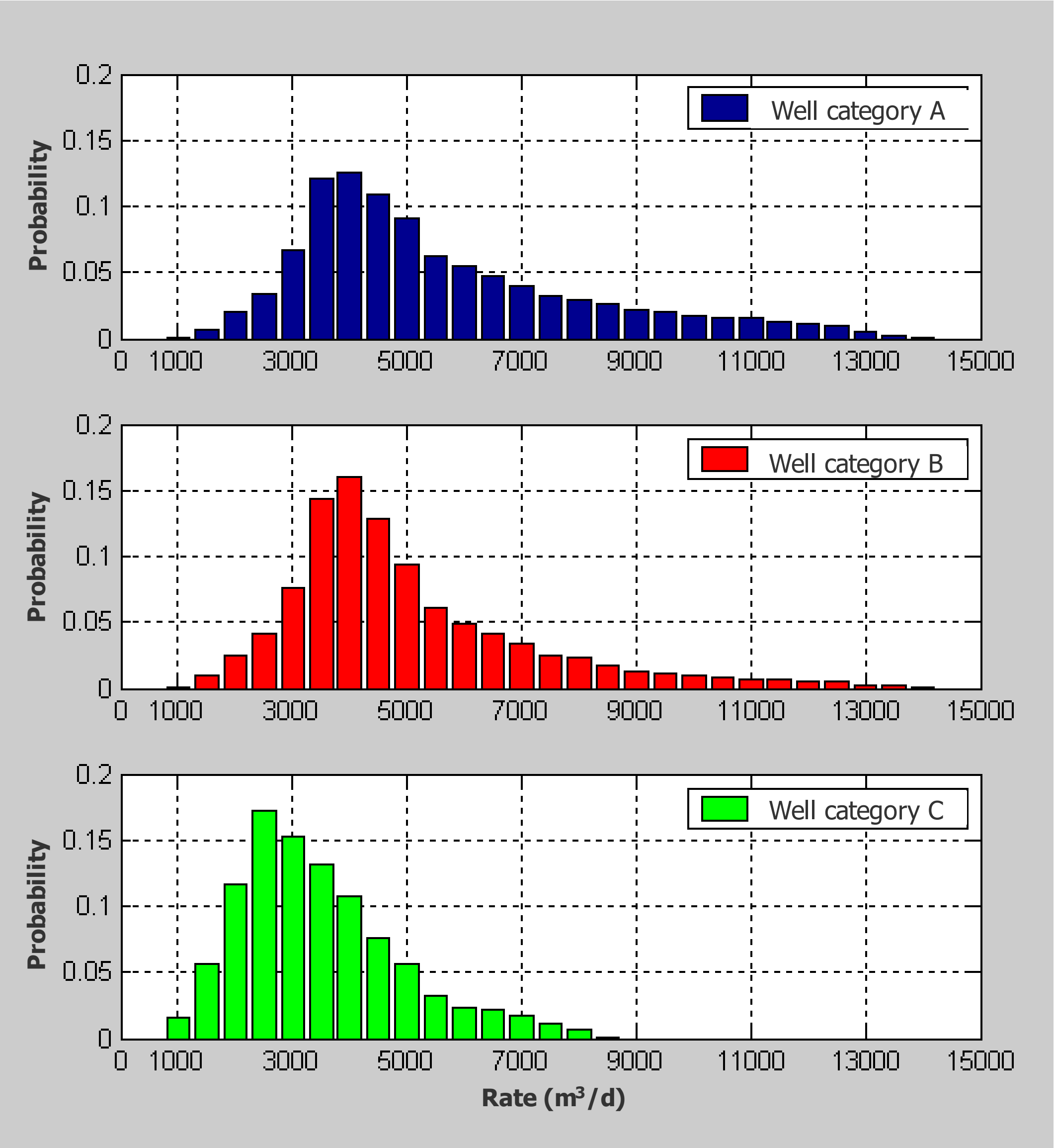

Figure D.24 Specific rate distributions for the three well categories.

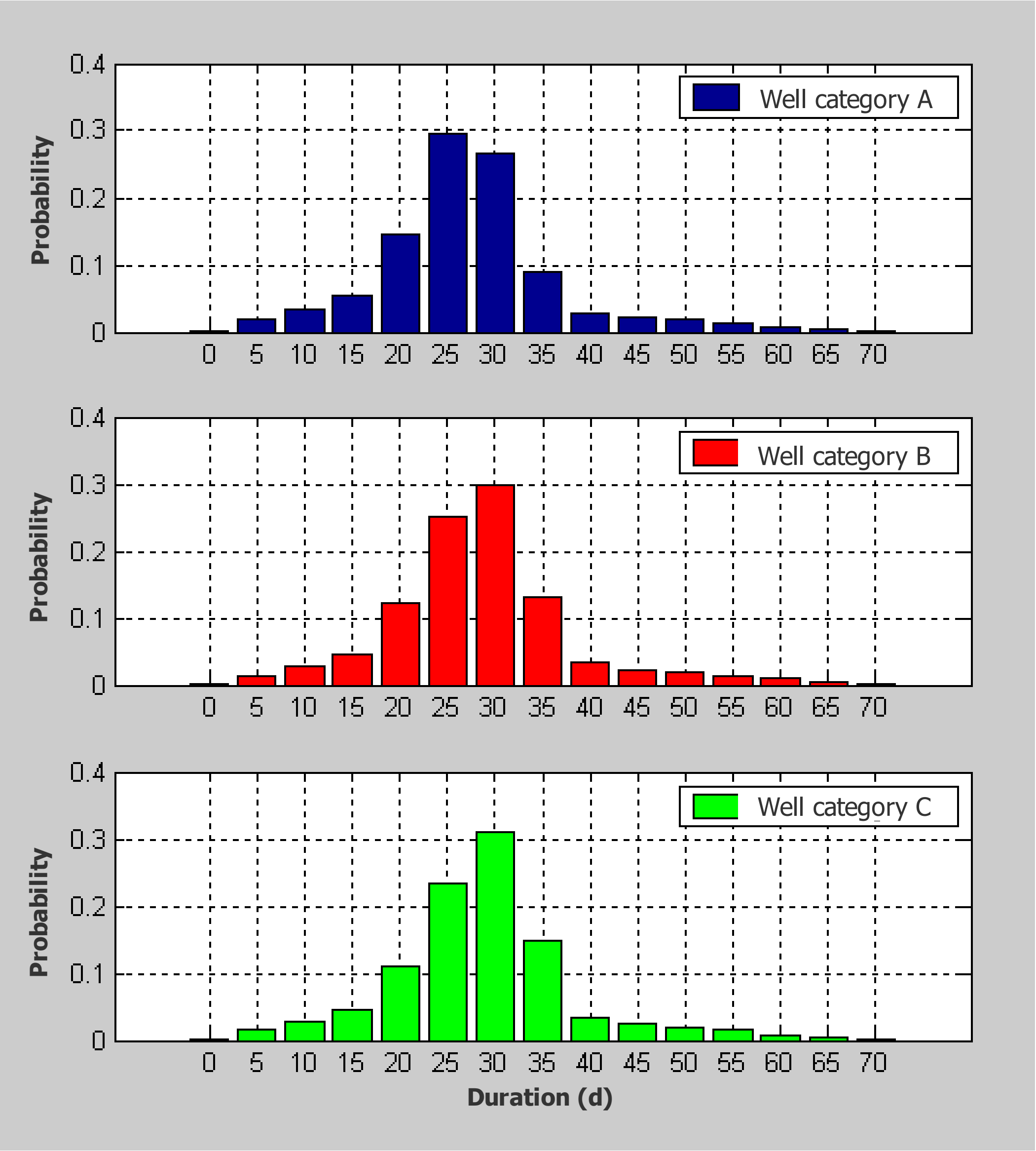

Figure 2.25 Specific duration distributions for the three well categories.

D.3.5 Additional assessment at C level of detail

The calculations so far are a combination of the A and B levels of detail, as outlined at the beginning of this example. What is the consequence of using simplified calculations at level C? A typical approach would be to use the 90th percentile from the rate and duration distributions for the most unfavourable operation type. If drilling is used – see the uppermost section of figures D.23 and D.24 – that corresponds to a rate of 11 618m^3/d and a duration of 39.1 days. This yields a total volume discharged of 454 264m^3. Compared with the 90th percentile in the volume distribution based on levels A and B, which is 236 070m^3, this means that the simplified approach in this case produces almost a doubling of the volume discharged. Note furthermore that, if the calculation of volume discharged for the individual operations had been calculated in a more refined manner, as illustrated in figures 4.2 and 4.3, the difference would have been substantially greater.

SUPPLEMENTARY REPORT

DATA BASIS FOR BLOWOUT RATE SIMULATIONS

This supplementary report is intended to provide guidance for those involved with data collection for and/or simulation of blowout rates to be used in environmental risk analyses. It seeks to give an overview of data requirements and how the parameters may affect the results for various flow scenarios. The text is intended to supplement the main part of this guidance document on the treatment of uncertainty related to blowout rates and duration in environmental risk analyses (above).

1 INTRODUCTION

1.1 General

Calculating blowout flow rates forms part of the environmental risk analyses performed when preparing well activities in the Norwegian petroleum industry. Such analyses are required by the Petroleum Safety Authority Norway (PSA), enshrined in various regulations and described in greater detail in the Norsok standards.

A guidance document on calculating blowout rates and duration for use in environmental risk analysis was issued in Norwegian by the Norwegian Oil and Gas Association (formerly the OLF) in 2004 and revised in 2007. That document (above) has now been translated into English, updated and reissued by Norwegian Oil and Gas as guidance. The present supplement is attached to this guidance. It aims to help standardise important parts of the methodology and approach used in these analyses. Although the main part of the guidance document provides an overall description of factors influencing blowout rates and durations, the focus is on various modelling and probabilistic approaches to the treatment of uncertainty related to blowout scenarios, flow rates and durations. However, it does not address in detail the physics governing blowout rates and how various models may be applied for the actual rate calculations.

This supplement aims to meet the need for such guidance through a detailed description of the various input parameters for blowout rate calculations. These relate to simulation of the blowout rate for a given scenario with regard to model selection and considerations at the parameter level.

See the main part of this report for guidance on how to take account of uncertainty and to deal with probabilities related to input for or output from flow rate calculations or to the combination of multiple scenarios.

1.2 Governing documents, regulations and standards

The PSA issues regulations which govern safety and the working environment in petroleum activities on the NCS. These have been developed to serve as a tool for the industry and to facilitate good collaboration between those involved.

They include the framework [1], activities [2], management [3], facilities [4], and technical and operational regulations [5].

Norsok standards are developed by Norway's petroleum sector to ensure adequate safety, value added and cost effectiveness in industry developments and operations. Examples of these standards relevant for blowout rate calculations and environmental risk assessments are Norsok D-010 *Well integrity in drilling and well operations* [6], S-012 *Health, safety and the environment (HSE) in construction-related activities*, [7] and Norsok Z-013 *Risk and emergency preparedness assessment* [8].

As far as possible, Norsok standards are intended to replace internal oil company specifications and to serve as references in government regulations.

2 DATA REQUIREMENTS FOR MODELLING

2.1 General

Information from a variety of disciplines in the oil companies is required to model and run necessary blowout and kill simulations. Routines should be implemented for validating input data, and this process is very important in achieving a representative combination of scenarios and input. Poor quality of input data or simulation approach might result in an unnecessarily conservative allowance for contingencies and an overrating of risk. Another worst case could be insufficient contingency and underrating of risk. Multidisciplinary knowledge is needed to review and verify assumptions in the data basis and scenario selection.

The following sections describe some of the most important input parameters and how they will influence the calculations and results. Dependency on each parameter will vary from case to case, and generic conclusions cannot be drawn on the overall consequence on the outcome. Reservoir permeability may have a huge impact on the results in one case, for example, while being of limited importance for another. A sound understanding of reservoir properties and productivity, fluid properties, well design and multiphase flow is required to model and perform these simulations.

While the main application of the results from blowout rate simulation discussed in this document is environmental risk analysis, blowout rates are also used as input for the calculation of kill rates as part of blowout contingency planning. Although assumptions and input may differ somewhat, simulation of blowout rates for both applications is usually conducted as a single activity in order to save time and resources. The sections below occasionally mention some concerns relevant to kill simulations.

2.2 Well location

The location of a well does not have a direct impact on estimating blowout rate, but is important for blowout contingency plans. Relevant examples include the rigs available in the vicinity which can be used to drill a relief well, and determining relief well spud location. Two of the latter are required by the regulations. See section 86 on well control in chapter XV on drilling and well activities in [2] and sub-section

4.8.2 in [6]). Should a blowout occur, its duration will depend on the well location (including such factors as rig mobilisation time and the availability of special equipment and services). Furthermore, the location is an essential element in the risk of harm to environmental resources.

2.3 Water depth

Water depth will affect the calculation results indirectly through the back pressure applied to the flow in scenarios where the release point is at the seabed. It will also affect temperature calculations for surface blowouts.

Where blowout kill simulations are concerned, the riser margin will be important when designing the control operation. This is especially important with deepwater blowouts. The riser margin is the increase in mud weight needed to offset the loss of hydrostatic pressure from the mud when the riser is disconnected and the hydrostatic pressure of mud from the surface to the seabed is replaced by that of seawater.

2.4 Drilling rig

The drilling rig will indirectly affect the results through well design and configuration – in other words, drill pipe size and BOP. The type of rig (jack-up, semi-submersible or drill ship) will be important in assessing potential blowout scenarios and release points. Where blowout calculations are concerned, a distinction can be drawn between the following categories of units:

- jack-ups and fixed installations with a surface BOP
- semi-submersibles and other floaters with a subsea BOP.

Where wells have a surface BOP, the release point is at atmospheric conditions. Subsea wells with a subsea BOP can have a release point at either the surface (through the riser and drillpipe) or the seabed.

2.5 Reservoir fluids

In addition to well design and reservoir properties, the reservoir fluids are the most important input parameter for blowout rate calculations. A compositional approach is recommended in order to ensure their proper thermodynamic representation. Fluid properties vary with pressure and temperature, and an equation of state (such as SRK-Peneloux or Peng-Robinson) is often used to characterise the fluid and generate the required properties. See Figure 2.1. Applying the actual reservoir fluid compositions is important. Compositions originating downstream from a process are occasionally specified, and these cannot be used directly in the flow model. See the schematic of a separation process in Figure 2.2. In pressure, volume, temperature (PVT) reports, the composition to be used is often labelled as the recombined reservoir fluid. Where a composition is specified with a plus fraction, the mole weight and liquid density of the plus fraction are required to characterise the fluid.

Other fixed parameters can be supplied in addition to the fluid composition, such as saturation points, densities, gas-oil ratios (GORs) and viscosities. A mismatch can quite frequently be observed between these properties and the specified fluid composition. Since the fixed parameters are often based on various processes, such as laboratory tests, production samples and drill stem tests (DSTs), they do not correspond with the recombined reservoir fluid composition. A process on a production platform is usually designed to increase the amount of liquid and remove heavy components from gas. The GOR of a specific fluid, for example, may be 7 000 scm/scm after being processed on the production platform, while the single-stage flash GOR (simply releasing the reservoir fluid to ambient conditions, as happens in a blowout) is twice as high. The same discrepancy also arises for phase densities, viscosities and other fixed parameters.

Viscosity at reservoir conditions is a key parameter when calculating inflow performance relationships. Where an oil reservoir is concerned, doubling this parameter will reduce the productivity index by 50 per cent. Viscosity is as important as permeability and net pay in the Darcy flow model.

Saturation points (bubble points and dew points) should be verified. These are usually specified as equal to (equilibrium) or lower than reservoir pressure. Should the saturation point show a higher value than reservoir pressure, this finding should be questioned since it implies that two phases exist in the formation. If that is in fact the case, two separate compositions should be specified – a gas-cap fluid and a condensate or oil composition. Also note that more than one saturation point can exist for a given pressure or temperature. The entire phase envelope should be plotted and verified. An example is shown in Figure 2.3.

A simple PVT checklist which should be used as a minimum when establishing fluid compositions is presented below.

- Is the specified composition a recombined reservoir fluid?
    - Occasionally, the specified fluid composition is taken from the liquid drain from a test separator.

- Does the specified GOR relate to a single-stage flash at standard conditions?
    - This is usually not the case. The GOR is often reported at a given pressure and temperature, and is quite often specified on the basis of a given process.

- Other “tuning” parameters. Do liquid density and saturation points match?
    - Saturation points can supply valuable information. Specified liquid densities are often inconsistent with the reservoir fluid composition.

Should a compositional analysis of the fluid not be obtainable, an alternative is to use black oil correlations for property generation. Minimum inputs for these empirical models are densities and GOR for a given process (single-stage flash) at a given condition (one atmosphere and 15°C). A number of black oil correlations exist in the literature. However, all have limitations compared with the compositional approach. They are based on the assumption that an oil with given gravities in the liquid and gas phases will have a fixed gas solubility and a formation volume factor at a given pressure and temperature. An implication of this assumption is that the oil and gas composition does not change with pressure and temperature, and black oil correlations are unable to predict retrograde condensation. They are therefore not recommended for light volatile oils or gases.

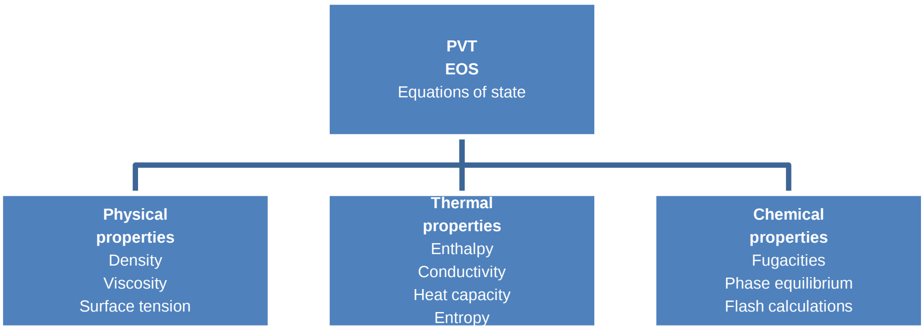

Figure 2.1: Equation of state and PVT properties.

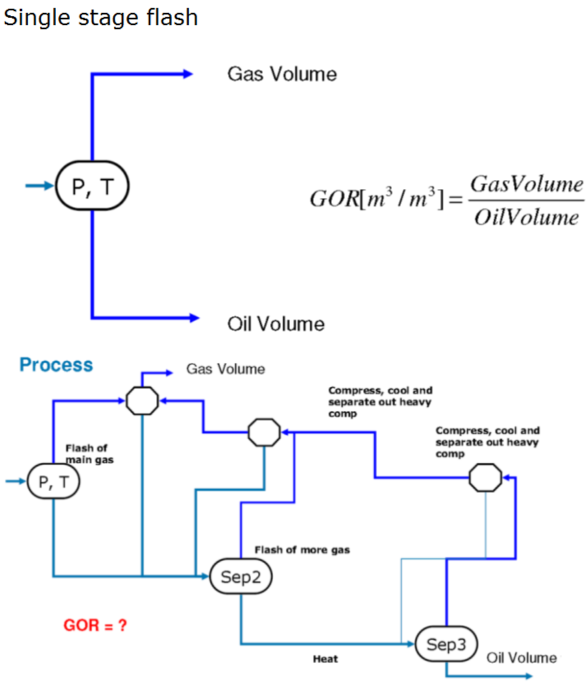

Figure 2.2: Single-stage versus process GOR.

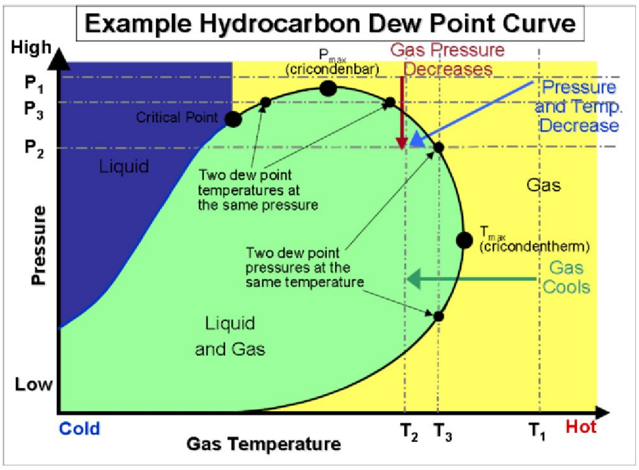

Figure 2.3: Example of a phase envelope.

2.6 Reservoir data

In addition to the reservoir fluid (viscosity), reservoir data are important for calculating the inflow performance relationship (IPR). Non-linear or quadratic relationships should be used for gases, and for oils below the bubble-point pressure. The IPR can be supplied directly or it can be estimated on the basis of a set of input parameters.

The IPR is quite often specified with a certain productivity index (PI). Using a linear relationship for blowout simulations is not generally recommended. This is because a blowout often yields large drawdowns and flowing bottomhole pressures below the bubble point. A linear PI does not take turbulent skin effects into account and could therefore overestimate the blowout potential. The linear approach is sufficient for a production scenario with moderate drawdowns and pressure above the bubble point.

Common practice is to model the IPR as a pseudo steady-state flow in a cylindrical region. This means that the pressure transient has hit the outer boundary of the reservoir and that the pressure is declining from the outer boundary towards the wellbore. A typical Darcy flow equation for liquid is given below.

$$q = \frac{kh\Delta p}{141.2\mu B\left(\ln\left(\frac{r_e}{r_w}\right) + S - 0.75\right)}$$

where
k - *horizontal permeability, mD*
h - *formation net pay, ft*
Δp - *pressure differential from outer boundary to wellbore, psia*
μ - *oil viscosity, cP*
B - *formation volume factor, rb/stb*
Re - *radius of investigation, ft*
Rw - *wellbore radius, ft*
S - *mechanical skin, -*

An example of a non-linear IPR typically used for gas reservoirs is shown below.

$$P_r^{\,2} - P_{wf}^{\,2} = \left(\frac{T\mu_g z}{0.703kh}\right) \cdot \left(ln\left(\frac{r_e}{r_w}\right) - 0.75 + S + DQ\right) Q$$

where
Pr - *reservoir pressure, psia*
Pwf - *flowing bottomhole pressure, psia*
μg - *gas viscosity, cP*
z - *gas compressibility, -*
T - *reservoir temperature, °R*
Q - *gas rate, mmscf/d*
D - *turbulent skin, 1/mmscf/d*

2.6.1 Reservoir pressure

The reservoir pressure should be specified as a gradient or an absolute pressure at a given depth. Pressure distribution within the reservoir zone is determined by the hydrostatic head created by the reservoir fluid.

Reservoir pressure can vary with time and might deplete during the time frame of a blowout. If that is the case, an averaged blowout rate can be estimated for spill volume calculations. Where relief well kill operations are concerned, the depleted reservoir pressure can be used for the kill simulations at the estimated time of intervention. Since the rate of depletion depends on a number of mechanisms with a high degree of uncertainty, however, the initial reservoir pressure should still be taken into account in kill simulations and contingency planning.

2.6.2 Fracture pressure profile

A fracture pressure profile is required in order to evaluate crossflow potentials and to design a kill operation. These profiles can be used for scenario determination, such as the potential for a kick breaking down a casing shoe with subsequent evaluation of the potential for a crossflow. The pore and fracture pressure profiles are usually presented in the same chart and collectively represent the drilling margin for the well – in other words, the lower and upper boundaries for the mud weight to be used.

2.6.3 Reservoir temperature

The reservoir temperature should be specified, or alternatively a profile established from the seabed through the various sands and reservoirs. The reservoir temperature will affect the temperature and thereby the properties of the fluid flowing through the wellbore. The ambient temperature profile (often implemented as a linear gradient from the seabed) is also important for the simulations.

2.6.4 Permeability

Permeability is a measure of the ability of fluids to flow through rock (or other porous media) and represents an important parameter in Darcy's law. Reservoir permeability can be estimated using various techniques, such as core analysis, well testing and continuous wireline well-log correlations. Permeability derived from wireline logs is often presented in a plot showing values versus depth in the productive sands. In order to specify a mean value, the permeability log should be integrated over the net pay sands in the reservoir. This is usually done automatically by the software. The equation for deriving an arithmetic mean of the permeability is shown below.

$$k_{avg} = \frac{\sum_{i=1}^{nz}(k_i h_i)}{\sum_{i=1}^{nz} h_i},$$

where

k_{avg} = *arithmetic average permeability*
nz = *number of layers*
k_i = *permeability for a given layer*
h_i = *thickness of the given layer*

The maximum permeability in the wireline log is often very high. However, this value is not representative for a large pay thickness and should not be used, since that would result in an unrealistically high inflow performance. The maximum value should be regarded as a maximum averaged permeability for the pay zone.

The variation in the permeability versus depth should also be taken into account for the scenarios which assume that only the top of the reservoir is exposed. The latter may have permeabilities which differ from the average value over the entire reservoir. Both horizontal and vertical permeability should be specified. Vertical permeability is especially important for partly penetrated reservoirs.

2.6.5 Reservoir thickness, net to gross and net pay

Net pay is the part of a reservoir, or its net thickness, from which hydrocarbons can be produced. The difference between gross and net pay is established by applying cut-off values in the petrophysical analysis, and can be determined from such sources as resistivity logs. Net pay provides input to the reservoir inflow performance and has the same impact as permeability in the Darcy flow model. It cannot be larger, and is usually smaller, than the total reservoir thickness. If the net to gross ratio is unknown, 100 per cent can be assumed as a conservative approach.

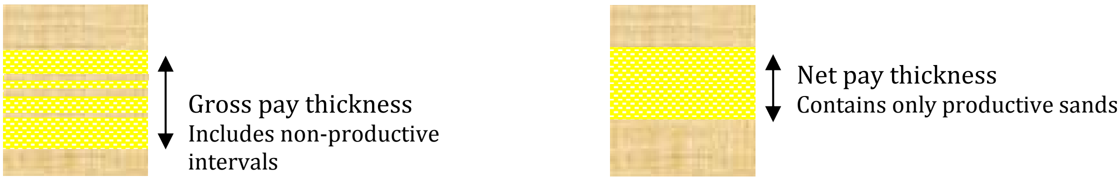

Figure 2.4: Illustration of difference between gross pay and net pay sand.

2.6.6 Skin effects

The skin factor incorporates all aspects of near wellbore performance, both positive and negative, including formation damage, perforation, gravel packs, stimulation and hole angle. The mechanical skin is often a measure which takes account of reduced permeability in the near wellbore area, usually resulting from the drilling operation and damage to the wellbore. A value of zero is typically used for contingency purposes if no other figure is specified, and indicates no restrictions ([6] states that zero should be used). An initially positive skin can be reduced to vanishing point during the blowout.

Where scenarios assume a partly penetrated reservoir, part skin penetration should be calculated (using the Brons & Marting correlation [9]), for example). With deviated wellbores, a negative deviation skin can be applied when modelling the reservoir as a single inflow point (using the Besson correlation [10], for example).

The different components of the skin factor are interlinked. Adding the skin value components is not generally possible. Where the combination of mechanical with completion skins (deviated, partially penetrated or horizontal well) is concerned, Pucknell and Clifford [11] provide a simple method for combining the skin factors.

2.6.7 Turbulent non-Darcy skin

Non-Darcy flow is typical for high-rate gas wells. The flow converging to the wellbore reaches velocities which exceed the Reynolds number for laminar flow. The result is turbulent flow. Laminar flow in the formation is assumed for the Darcy relationship, and the turbulent effect is implemented with the rate-dependent skin factor.

A new turbulent skin value should be calculated for scenarios which assume a partly penetrated reservoir.

2.6.8 Reservoir drainage area

The reservoir drainage area is an input to the inflow performance relationships, usually as an effective drainage radius for radial flow – in other words, the outer boundary for the pressure drop towards the wellbore.

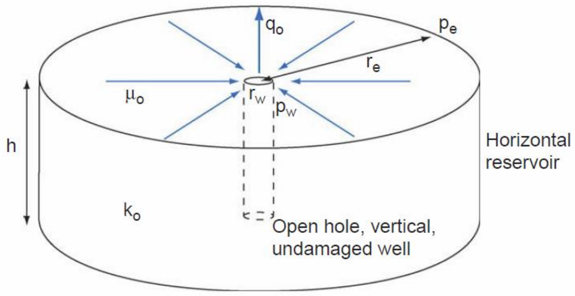

Figure 2.5: Radial inflow flow.

2.7 Well configuration and casing design

The well design should be specified with tubular dimensions (casings, liners, tubings, drillpipe, bottom-hole assemblies), set points and hole sizes. The planned well design is an important input to the scenario selection process and the multiphase flow calculations. Larger flow conduits usually yield higher flow rates, but not necessarily. In low-rate conditions, larger flow areas can accumulate more liquid and result in a higher hydrostatic head and lower flow rates. Where narrow restrictions exist in the flow path and at the release point, checking for sonic velocity is important since this will limit the flow rate.

3 REFERENCES IN SUPPLEMENTARY REPORT

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