HYDRATE CONTROL FOR GAS STORAGE OPERATIONS

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Final Report

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RESEARCH SUMMARY

Title: Hydrate Control for Gas Storage Operations

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Objective:
The overall objective of this project was to identify low cost hydrate control options to help mitigate and solve hydrate problems that occur in moderate and high pressure natural gas storage field operations. The study includes data on a number of flow configurations, fluids and control options that are common in natural gas storage field flow lines. The final phase of this work brings together data and experience from the hydrate flow test facility and multiple field and operator sources. It includes a compilation of basic information on operating conditions as well as candidate field separation options. Lastly the work is integrated with the work with the initial work to provide a comprehensive view of gas storage field hydrate control for field operations and storage field personnel.

Technical Perspective:

Hydrates cause gas storage field operational problems that can affect gas deliverability to customers most on days when demand for gas storage services is highest. Finding and eliminating a hydrate blockage in storage field flow lines and equipment can take several days, with much of that time spent trying to isolate the blockage location. In that time period, operators can miss market significant opportunities. Traditional hydrate control and hydrate remediation technologies are expensive to implement and can increase disposal costs due to environmental concerns of the hydrate inhibitor.

Hydrate problems are not restricted to high demand cold operating periods. They occur throughout the year due to the operating conditions in the flow lines. Whenever hydrates create flow constrictions and blockages they will affect the ability to deliver natural gas from a gas storage facility.
Results:

The project has provided a number of results and insights for hydrate control for gas storage field operators. It has identified low cost hydrate control methods using traditional field equipment and techniques to accomplish it.

Results from this research study provide storage facility operators with practical hydrate control data. The data demonstrate how hydrates are formed, transported, and accumulate in gas storage field flow lines under a variety of operating conditions and scenarios. The research data further identifies the importance of monitoring key operational variables for hydrate monitoring and control. The data are based on measured experimental data with hydrates in the flow lines that simulates similar gas storage field operating conditions.

The experimental data are used to develop recommendations that permit storage field operators to:

- optimize the use of hydrate control chemicals, such as methanol to control, prevent, and eliminate hydrate blockages,
- modify operating procedures, during shut-ins and start-ups to control the impact of hydrates,
- improve system design by eliminating oversized flow lines,
- improve data collection and data monitoring to improve hydrate control in the field,
- inform field personnel of operating practices that may lead to hydrate problems.

In addition, the research work has enabled development of a full-scale hydrate flow test facility. The test facility provides the basis for tracking the in-situ thermodynamic and fluid dynamic behavior of hydrates:

- non-isothermal hydrate flow studies for surface flow lines and equipment in the presence of water, hydrates and chemical inhibitors,
- isothermal hydrate flow studies for sub-surface flow line and equipment flow study evaluation in the presence of water, hydrates
and chemical inhibitors, i.e. simulated isothermal operation conditions,

- condensing flow data for non-isothermal and isothermal studies in the presence of water, hydrates, and chemical inhibitors,
- high pressure hydrate flow studies in the presence of water, hydrates, and chemical inhibitors,
- hydrate flow studies in the presence of water, hydrates, and chemical inhibitors, on sloping terrains,
- hydrate flow studies in the presence of water, hydrates, and chemical inhibitors, in well-bores.
- hydrate transport studies.

Technical Approach:

This study began by obtaining representative storage field data to identify critical variables during periods when hydrates were known to cause problems in the field. The variables identified the prevailing thermodynamic and fluid dynamic operating conditions responsible for hydrate formation, transport and blockage development in gas storage fields. The field data provided the basis for controlled tests at the CEESI hydrate flow test facility.

Hydrate flow tests were conducted to simulate field operating conditions and to investigate hydrate formation, deposition, transport, inhibition, and remediation under controlled laboratory conditions. Video monitoring was extensively in order to obtain cross-sectional and axial views of hydrate behavior in the test facility flow lines. The video data provided visual evidence on the mechanisms of hydrate formation, agglomeration, transport, accumulation, and blockage development under typical gas storage field-like conditions. It was also used to investigate the impact of traditional remediation methods, i.e. methanol drips vs. alternative methanol treatment methods. The volume of video data is problematic due to the time required to edit the images.

Two storage field operators contributed to the study by providing field sites where production and gathering flow lines were instrumented for real time data collection. Key elements of the field piping configurations were duplicated at the hydrate test facility location. Multiple series of tests were
Flow constrictions and flow blockages caused by natural gas hydrates, ice and water create economic, maintenance, and serious safety concerns for storage field operators. The problems manifest themselves in a reduction in gas deliverability, field efficiency and jeopardize downstream activities.

The results from this project have added significantly to the gas storage industry's understanding of how hydrates behave in gas storage field flow lines. It has opened up a greater understanding of hydrate transport and deposition dynamics under realistic field operating conditions. The data has identified shortcomings in hydrate control and remediation methods. It has also identified, through the hydrate flow data, a flow mechanism that may facilitate field efforts to control and remediate hydrates. Lastly, for the first time, it has documented the development and creation of in-situ hydrate plugs. This is particularly noteworthy. The understanding of the mechanism opens up a very important avenue for data and knowledge utilization.

Successful understanding and application of the results from this project will provide field storage operators the means to optimize hydrate control strategies, reduce inhibitor costs and quantities, improve flow line designs, minimize hydrate constrictions and blockages, and most importantly, improve safety for field workers. Such improvements in the field will provide the basis for improving deliverability from facilities that operate in hydrate prone environments.
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1. Study Overview

Hydrates have a history of creating flow problems in the gas industry. The purpose of this report is to provide natural gas storage field operators hydrate flow data obtained at flow conditions that mimic their field conditions to help them control hydrate blockages in the storage facilities. It has used gas storage field data from two storage fields (Latigo and Greenlick fields) to identify the flow and operating characteristics that cause hydrate problems in the flow lines. It has applied the experience and data from storage field systems and operators to identify appropriate full-scale laboratory tests that could be made under controlled variable conditions. The field and laboratory data have been used to identify appropriate strategies for hydrate control and detection in gas storage fields.

A hydrate flow test facility was designed, constructed and developed to simulate the conditions that produce hydrate flow blockages in gas storage field facilities. It includes isothermal, non-isothermal, high pressure, horizontal, slope, and well-bore pipe configurations and conditions. The test facility provides control of critical variables that impact hydrate formation, flow, blockage, and inhibitor control.

This report provides experimental flow data that were obtained from the field and the hydrate flow test facility. The data has helped identify many important features of the hydrate problem that are necessary to understand in order to control hydrate deposition and blockages in the field. The report focuses on empirically categorizing hydrate flow characteristics and problems under simulated gas storage field flow line operating conditions.

The empirical flow data obtained were under controlled conditions. The data provide measurements on the formation, deposition and transport of storage field hydrates in flow lines. It also includes data on the monitoring of hydrate blockage development and blockage control. The data are used to demonstrate pre-emptive actions and operator control options that can be taken to minimize and control hydrate blockage development. The suggestions should help operators reduce hydrate constrictions and blockage occurrences in the natural gas storage field thus providing the opportunity to improve safety and operating efficiencies.

Much of the test facility data is actual video data of hydrate formation, hydrate transport and flow blockage development in the pipe. This data is coupled to the operating conditions in the flow line. The video demonstrates hydrate transport and deposition phenomena and the effect of standard remediation efforts vs. proposed remediation efforts. The project has helped to demonstrate the need and feasibility of utilizing better hydrate control strategies.

The report identifies how field operating parameters and procedures impact hydrate formation, deposition, transport, blockage development, and inhibitor distribution. It suggests low-cost operating solutions that may be implemented in the fields as
automation is brought to well locations and flow lines here hydrates are known to cause problems. Some of the operating suggestions for storage field operators are as basic as including temperature and pressure measurements at or near locations where hydrates are known to cause problems and to blow down drips at intervals corresponding to the quantities of liquids produced and measured at the separator. Other suggestions are less obvious. They are based on the experience obtained with the testing during the R&D program, e.g. controlling the flow to create a specific flow regime for good hydrate inhibitor distribution.

1.1. Report Organization

The report begins with a general technical description of hydrate issues as they pertain to gas storage field fluids. It then moves to the practical implementation and implications of this knowledge in current gas storage field operations.

The remainder of this section provides a description of the experimental facility that is used to investigate hydrate formation, deposition, accumulation, and remediation for natural gas storage systems. This includes a description of CEESI's hydrate flow test facility including (1) isothermal test section, (2) non-isothermal test section, (3) horizontal flow section, (4) slope flow test section, (5) high pressure test section and (6) the well-bore test section. Each test section, and the associated data from that section, has provided useful data and insight, under controlled conditions, for hydrate control in the field.

The next section of the report details general lessons learned about hydrate formation, transport and blockage development from the field and hydrate flow lab test data. It begins with a discussion of hydrate chemistry, relative to storage field fluids, hydrate equilibrium diagrams, and the dynamic processes that control hydrate growth, transport, and accumulation to form blockages. The appendix provides a series of hydrate flow diagrams for a number of gas storage fields and flow lines that were utilized during the course of this work. The conditions cover both low, moderate and high pressure flow line and field conditions.

The third section of the report discusses general lessons learned about hydrate inhibition and control. This section also addresses hydrate chemistry as it pertains to hydrate inhibition and control, the effects of methanol and other inhibitors on the hydrate phase diagrams, inhibition effectiveness for systems containing free water and condensed water, and hydrate monitoring considerations.

The fourth section of the report takes the general lessons learned and applies them to real system constraints. It contains discussions of determining the susceptibility of various parts of a storage system to hydrate formation, practical inhibition/control issues, and blockage removal issues. It provides a flow diagram that may be used as a guide to facilitate implementing fluid and hydrate monitoring and control systems in
the field. This section also includes practical examples from storage field operators who contributed to the study.

The final section presents important conclusions and recommendations learned from this study. The recommendations should help provide the industry direction for future storage field operating improvements.

2. Practical Applications

2.1. General Overview

Flow constrictions and flow blockages caused by natural gas hydrates, ice and water create economic, maintenance, and safety problems for storage field operators and personnel. The problems manifest themselves through gas deliverability, field efficiency, flow line integrity constraints, and safety concerns. Hydrate blockages are the result of the interaction of natural gas and liquid water in the flow lines.

Hydrate problems are not restricted to high demand cold operating periods. They occur throughout the year due to the operating conditions in the flow lines. Whenever they create flow constrictions and blockages they will affect the performance of the storage facility and limit the ability to respond to gas control, business opportunities and changing market conditions.

At the base of the hydrate problem is a problem with water control and water management. Water creates a range of problems in addition to hydrate problems. In addition to flow line obstructions, the problems water creates include corrosion, flow integrity concerns, scale deposition in the flow lines, and inaccurate flow measurement among others. Hydrate control and management is an operational barometer on the condition of the producing wells and the downstream flow lines and equipment.

A clear understanding of how, when and where water is produced and transported under various operating and flow-line scenarios is a key element in identifying, managing, reducing and eliminating hydrate problems. The challenge of hydrate control needs to be put in the context of other operating and capital priorities at the time when other problems are occurring.

2.1.1. Economics

Depending upon the location of the blockage significant revenue may be lost during high demand periods when hydrate blockages occur. Demand charge refunds may be imposed on storage field operators if gas deliverability is
constrained. Residential, commercial and industrial end-users cannot afford peak delivery interruptions due to weather and process conditions. As gas demand pressures increase and field automation efforts extend to more gas storage fields, there is a growing need for the ability to detect, control and manage hydrate accumulations and blockages in the gas storage field. Operators may incur regulatory losses due to inadequate deliverability. Loss of peaking deliverability is the lost sale of high value peaking gas.

2.1.2. Safety

Hydrates in flow lines may expose storage field personnel to a number of conditions that require special safety considerations. Although rare in gas storage field operations when hydrates are present there is the potential for an unsafe operating condition due to the complexity of hydrate deposition and blockage development. These conditions arise due to the basic chemistry and flow dynamics of natural gas hydrates and its related fluids, the operating conditions in the field, and the presence of water in the well-bore, flow lines and related equipment.

The operating conditions which create the potential for hydrate deposition on pipe walls, in-line equipment, and on free liquids create complex accumulations of hydrate solids and semi-solid masses. The accumulations depend on both the ambient conditions (for exposed pipe), subsurface pipe conditions and the operating conditions, e.g. shut-in, start-up, injection or withdrawal. The formation of hydrate blockage is a three phase flow problem, i.e., gas, liquid and solid coupled to crystallization and agglomeration kinetics. In general this type of problem is a difficult problem. The blockage may not be a single blockage but consist of multiple distributed hydrate mass accumulations and blockages. Decomposition of one blockage can create problems with other blockages. Although we can predict the temperature, pressure, and composition conditions of hydrate formation, predicting the dynamic flow behavior of hydrate masses and identifying the location and time when a blockage will develop is beyond current modeling capabilities. Consequently, the safety practices are based on industry wide experience with gas hydrates blockages over many years.

There are many known instances in the energy industry where hydrates have caused significant safety problems. Gas hydrates can become an operating safety concern to personnel and equipment due to the potential for rapid hydrate decomposition or hydrate mass dislodging and the subsequent release of large amounts of high pressure gas from the hydrate crystalline structure. Methods used to decompose hydrate plugs can also produce high differential pressures across a hydrate mass that will cause the hydrate mass to act as a high velocity projectile inside of the flow lines. Industry experience has demonstrated that these can produce equipment and personnel damage. Personnel should always consult their company’s safety officer regarding procedures with natural gas hydrates.
2.1.3. Efficiency

Wherever water is present there is a good chance that hydrates are present. Water management, hydrate formation and hydrate plug control provides a good internal indicator of the operational condition of storage field flow lines. The presence of substantial hydrates indicates that there is a large amount of free liquid in the flow lines or that the hydrates have accumulated on pipe walls over a period of time. The presence of the free liquid is a precursor to the potential development of a number of problems including hydrates and corrosion.

Controlling water and hydrates helps to maintain the pipeline integrity and reliability of the gas storage field and operating system. In addition, improved water management prior to the water entering the pipeline network will lead to a reduction in dehydration requirements, maintenance and operating costs.

2.1.4. Environment

The most practical chemical means to control hydrates in gas storage fields is to use a chemical inhibitor like methanol to shift the liquid phase composition operating conditions at which hydrates will form. Methanol could be potentially toxic to the environment and water supply. Methanol is the most viable control blockage control option for gas storage fields and is clearly needed to either prevent hydrates from forming or to help decompose flow line blockages caused by hydrates. Better water management leads to a significant reduction in the need and use of methanol for hydrate control.

2.1.5. Operational Knowledge

A knowledge of the locations of hydrate formation, transport, constrictions, and blockages provides insight into the complex dynamics of flow throughout the gas storage system. These points are locations that are sensitive to the operational dynamics and their effect on the internal gas flow velocity dynamics of the pipe network and the associated liquid and hydrate solid transport and deposition throughout the network.

2.1.6. Maintenance

In addition to constricting and blocking flow lines and requiring significant quantities of methanol, hydrates cause maintenance problems in the well tubing, the valves, the surface equipment including the instrument lines, meters, damage to equipment, drips, methanol pumps, and damaged liquid turbines.
2.1.7. Personnel

Hydrates require the attention of field personnel and operators since hydrates will disrupt or inhibit the flow of gas to the pipeline system. Hydrates problems require time to identify and remediate. Typically field personnel do not have the time that is required to fully address a hydrate blockage. Decomposing hydrate blockages via depressurization can require days. Winter conditions may exacerbate the blockage problem. Historical practices may create safety concerns for the personnel under certain blockage situations. The usual procedure is to shut-in that portion of the flow-line where the hydrate plug is located and to address the problem at a later time when more time is available and gas demand from gas control is low.

3. Experimental Facility Description

The CEESI hydrate flow test facility was developed to obtain data on the behavior of natural gas hydrate blockages in flow lines. The facility consists of multiple test sections. Each test section permits investigating different aspects of the hydrate flow and blockage problem. The fluids that are used in the test loop to study natural gas hydrates include natural gas, water, condensate, and inhibitors such as methanol.

3.1. Test Facility Overview

The test facility consists of three different test loops. Each test loop has multiple test sections where data are acquired during a particular test run. The test loops operate under a wide range of operating conditions that are used to simulate storage field operating conditions. Two of the loops have operating pressures up to 1440 psia, one has an operating pressure up to 3400 psia. Depending on the type of test, the test loops can operate independent of each other, however this is difficult to achieve in practice due to the complexity of the testing. Figure 1 provides an overview of the area at the CEESI lab that is used for hydrate flow tests.
Figure 1. Overview of the CEESI Hydrate Flow Test Facility area.

Figure 2 shows the three sections of the hydrate flow loop. The view is to the south of the CEESI facility. In the background, at the south-end of the test facility is the non-isothermal hydrate flow loop. In the middle of the image behind the condenser is the isothermal test section and to the right of it is the high pressure test section of the hydrate flow test loop. In the foreground of figure 2 is the wet gas test loop.

Figure 2. Overview of the CEESI Hydrate Flow Test Facility area showing non-isothermal loop, isothermal test loop, and high pressure test loop areas.
The hydrate flow test facility consists of multiple 4" flow lines with different configurations, system controls and data acquisition facility, pressure and temperature transmitters, flow metering, on-line sampling, liquid control and knockouts, steam injectors, horizontal separators, condenser, chiller, water and hydrocarbon injection tanks, vertical and mist separators, and a dehydration unit. A single compressor provides the ability to obtain gas velocities up to approximately twenty feet per second. Higher gas flow rates are possible.

Figure 3. shows the hydrate, wet gas, and natural gas flow facility control room. On the upper right hand side of the control panel is a monitor, located between the two windows, which has a live view of the flow conditions from a video camera recording the test that is in progress.

Figure 3. Wet gas and hydrate test facility flow control and data acquisition.

The hydrate test facility operates with a wide range of gas and liquid flow rates. Figure 4 shows the hydrate flow test facility operating range superimposed over the liquid water, hydrate and ice operating zones.
The pressure, temperature, and composition operating range of the test loop ranges from pressures up to approximately 3400 psia, temperatures range from ambient conditions that approach 0 °F up to 110 °F. The composition of the natural gas depends on the gas supply provided to the test loop from the pipeline. The facility can produce different composition blends for flow testing.

Figure 4. Hydrate flow test facility operating temperature and pressure region.

The hydrate flow test facility simulates storage field flow rates. Flow rates range from low flows, similar to those to the field data location at Latigo and Greenlick storage fields of approximately 4MMSCF per day, to flow rates exceeding 20MMSCF per day. Figure 4 shows that the operating conditions for each test are within the range of operating conditions that are commonly encountered in gas storage field equipment and flow lines when hydrates problems are known to be present in the field.

The hydrate test facility has the capability to handle most fluids that occur in the gas storage field including condensed and produced water, produced condensate fluids and hydrate inhibitors. The amount of each fluid in the flow line impacts the rate of hydrate formation, transport, deposition and accumulation characteristics.

Under normal operation the test loop is used to simulate gas cycling periods including gas injection, gas shut-in periods, withdrawal, liquid transport, hydrate transport, hydrate blockage development, hydrate inhibitor injection, and start-up conditions.
As mentioned earlier, there are three independent sections in the hydrate test loop. Figure 5 provides a simplified block diagram of two of the test sections, the non-isothermal test section and the isothermal test section. These sections operate at pressures less than 1400 psia. The diagram illustrates the standard components used to achieve gas and liquid flow and temperature control in the hydrate test loop.

**Figure 5. Simplified block diagram of the 4” non-isothermal test and isothermal hydrate flow test sections.**

In general, a hydrate test consists of establishing a flowrate condition that approximates the flow environment and operating conditions at the Latigo and Greenlick field sites, typically these flow rates are less than five ft/sec although this will vary depending on the physical condition in the line. A by-pass valve establishes the pressure drop across the test section. Flow is controlled in the test sections to simulate steady and unsteady state flow conditions that occur during start-up, normal withdrawal and injection operations, shut-in, and blockage development periods.

Figure 6 provides a more detail view of the non-isothermal and isothermal test sections of the loop. It illustrates instrumentation locations where data may be obtained during any particular test. The typical instrumentation includes temperature transmitters, pressure transmitters and dp transmitters.
Figure 6. P&ID diagram of the 4" non-isothermal test and isothermal hydrate flow test sections.
3.1.1. Non-Isothermal Hydrate Flow Loop

The first section of the hydrate test loop is the south test loop. It is a 4” nominal diameter non-isothermal loop. Figure 7 provides a view of this section of the test loop. The view is looking east, with gas flow in the direction towards the viewer. This test loop permits obtaining hydrate data for surface flow lines at low ambient temperature conditions.

Figure 7. Southleg view of 4” non-isothermal hydrate flow test section.

The non-isothermal hydrate testing section is approximately 130 ft. in length. Seven discrete locations are used to obtain data that simulate gas storage flow line behavior. The test locations include: (1) section upstream of the first orifice fitting, (2) orifice meter and associated instrument line fittings, (3) section downstream of the first orifice, (4) cross-sectional viewing spool, (5) drip section, (6) section downstream of the drip section with cross-sectional bulls-eye windows for viewing, and (7) simulated blockage development section up and downstream of the senior orifice fitting. The non-isothermal test section is followed by a hydrate buster section and a catch tank.
Figure 8 provides a schematic that shows the major test section elements of the non-isothermal test section. Gas flow is from left to right. Many of the images provided in this report were obtained using the view port, at location 1 and in the test section’s bulls-eye windows located downstream of the ball valve and upstream of the Senior Orifice fittings.

Figure 8. Hydrate flow test section south leg test section schematic.

Gas, water, and hydrates flow towards the orifice meter situated above and to the left of the simulated drip in figure 8. Flow then drops and goes past the view port prior to the drip. The drip is located at the approximate mid-point of the loop. Flow continues to the right of the drip where it ascends a small 45° incline to the second flow blockage development test section. The second flow blockage development section of the isothermal loop is used for hydrate blockages in a controlled manner. It permits evaluating hydrate monitoring and hydrate remediation methods by controlling the transport of the hydrate mass through the test section. It accomplishes this by restricting the flow through the downstream orifice plate or by aging, i.e. shutting in, the hydrate mass that accumulates in the test section.

Figure 9 provides a view of the hydrate test facility viewing port spool section and the simulated liquid drip section. The viewing port provides imaging data on the hydrate mass during steady-state and transient operations. The view port provides a window for direct observation via video monitoring on the condition of the gas/liquid/hydrate in the flow lines. The use of video largely eliminates the need to infer the physical condition of the hydrate mass and fluid flow field.

The drip section is insulated and permits fluid injection, i.e. methanol and water, into the view port section. The liquid drip permits simulating the impact of liquid and hydrate build up in the drip location. It is also used to fill the view port with water, condensate and inhibitors.
Figure 9. Hydrate flow test section southleg cross-section viewport and drip.

Figure 10 is a cross-sectional schematic of the view port. The view port was used extensively to record hydrate behavior under flowing conditions with and without inhibitor.

Figure 10. Cross-section schematic view of hydrate flow viewing port.

In order to get more information on the flow condition, bulls-eye windows were installed on the test section downstream of the drip location. Figure 11 provides a view of one of the bulls-eye window installations. The bulls-eye windows provide the ability to obtain
discrete cross-sectional visual data as hydrate masses are transported by the flow downstream prior to and during hydrate blockage development. A video camera is used to monitor hydrate flow flow past the windows.

Figure 11. Bulls-eye windows located on the south-leg hydrate flow test section.

Liquid water, methanol and hydrocarbon can be injected at multiple points in the test section. For the isothermal test section water can be injected at the top of the riser shown in the schematic in figure 8. It can also injected downstream of the first orifice fitting. Water is also injected with or without methanol in the simulated drip section in the center of figure 8. The height of injected fluid is controlled by monitoring the view port section.

Water injected near the riser accumulates in the elongated u-shape section of pipe upstream of the first orifice fitting. The injected water creates pools by damming upstream and/or downstream of the orifice fittings. The degree of pooling depends on the gas flow rate. Liquid water pooling promotes a hydrate film to form on the surface of the water and promotes hydrate formation and blockage development both upstream and downstream of the orifice. Once hydrates have formed on the surface of the pool they can be carried through the orifice plate to downstream locations. As hydrates accumulate in this section of the test loop pressure builds behind the accumulated hydrate mass. Periodically the hydrate mass is flushed through by pressure into the view port and drip section where its movement is visually recorded. Similar behavior is observed in other test sections of the loop.
Flow rate disturbances, e.g. start-ups conditions, induce the hydrate slurries to flow through the orifice, viewport and downstream piping sections where they are videotaped. Pressure, temperature, composition and slurry appearance are monitored. Hydrate blockages are induced to form downstream of the drip location in the blockage test section by using artificial obstructions in the flow line helping to accelerate test times. These obstructions are used to obtain data on the flow and pressure behavior as hydrates are transported down stream and accumulate in a particular location in the flow line.

Figures 12 through figure 14 illustrate the installation of test equipment in the hydrate flow loop and evaluated during the hydrate flow tests. Figure 12 is a clamp-on ultrasonic meter was be tested for hydrate monitoring purposes on the test section of the non-isothermal test loop down stream of the view port. Figures 13 and 14 were to obtain data on hydrate crystal structures in the view port at flow line operating conditions.

Figure 12. Installation showing a Controlotron clamp-on ultrasonic on non-isothermal test loop.
Figure 13. Installation shows data acquisition and high magnification laser imaging on view port section of non-isothermal ontron clamp-on ultrasonic on non-isothermal test loop.

Figure 14. High magnification laser imaging system installation.
3.1.2. Isothermal Hydrate Flow Loop

The isothermal section of the hydrate flow test loop is included in the block diagram in figure 3 and the P&D of figure 4. The total length of this test section is approximately 80 ft. It is utilized to investigate the impact of condensing flow, shut-in, and start-up conditions on hydrate formation, deposition, transport and inhibition under conditions similar to subsurface flow lines.

Figure 15 provides an overview of the compressor and condensing units for controlling the flow and saturation in the isothermal test loop section. This test section includes steam injection, mixing, cooling and condensing, a liquid knock-out drums, flow by pass valves, fluid injection points for water and hydrate inhibitor, and fluid sensors used to monitor and control the condition of the fluid prior to it entering the test section. Temperature, pressure, and differential pressures are monitored at different locations in the test sections.

Figure 15. Overview of isothermal test section showing condenser and compressor.

Figure 16 shows the upstream area of the isothermal jacketed pipe test section. It is used for fluid and inhibitor conditioning upstream of the test locations. The white unit in
Figure 16 is the condenser. The gray unit next to it is the glycol chiller. The chiller controls the internal pipe wall temperature in the jacketed pipe. Free water and hydrate inhibitor are injected on the right side of the image to monitor the impact of these fluids on hydrates that have formed on the wall from condensation.

Figure 16. Condensing section of the isothermal hydrate flow loop test section.

In general, it takes a significant amount of time to run condensation studies in the test loop, i.e., days to weeks. Condensation studies are difficult because of the time required to obtain a significant build-up of hydrate on the pipe wall. Hydrate build-up due to condensation varies at different locations in the flow line with different flow rates. High flow rates shift the build-up to downstream locations.

In Figure 16, water saturated gas flows from the right side of the white test section in the image to the left. Visualization probes are inserted into the flow line to observe the tests in real time under varying flow conditions and fluid states, e.g., during start-up, steady state operations, shut-in, with and without inhibitor, etc.

Figure 17 shows the downstream test section of the isothermal loop. This section is used to evaluate hydrate blockage development as hydrate masses accumulate downstream of from the location of water injection and condensation. It is also used to evaluate the effectiveness of hydrate control methods.
A glycol chiller is used to control the temperature in the jacketed pipe sections. This permits pipewall temperatures approaching 40 °F. The heat transfer across the test section on the pipe wall is controlled by controlling the temperature in the jacketed pipe section. Methanol and water are injected downstream of the condenser.

Before beginning an isothermal test gas is usually saturated with steam before it enters into the condenser. This is accomplished through steam injection into the flow lines. The gas then flows through a mixer followed by a condenser where the temperature is significantly lowered. Excess water is removed at the exit of the condenser prior to entering the test section. The water saturated test gas then enters into the first jacketed pipe section which is maintained a constant temperature, typically between 40 - 55 degrees F.

The isothermal section of the test loop has a number of flow visualization options. A high pressure view port is located approximately mid-way through the test section, along with an orifice fitting. Axial visualization is also provided in this section of the loop. The axial viewing location is flexible. Temperature and pressure measurements are made at different locations along the isothermal test section. The flow rate can be obtained from
an orifice meter in the test section and from a turbine meter that is located on the return to the compressor.

The isothermal section uses multiple viewing options. These include a cross-section view port spool similar to the one in the non-isothermal test section, bulls-eye windows, and an axial viewing capability. The axial view is provided by a small probe that is inserted in pressure tap locations. Figure 18 shows the axial flow viewing probe. Many of the hydrate video images provided in this report are an axial view of the flow from the isothermal section of the hydrate flow test loop. The isothermal section of the test loop has been used extensively to study water and hydrate saturated gas flows at different flow rates under steady state and unsteady state conditions with and without inhibitor.

Figure 18. Isothermal test section axial flow viewing probe.

Figure 19 is an image of the IR instrument and data acquisition system that was used for monitoring the degree of water saturation in the isothermal and non-isothermal test sections. The IR instrumentation was provided by SpectraSensor.
3.1.3. **High Pressure Non-Isothermal Hydrate Flow Loop**

Figure 20 is a schematic of the high pressure section of the test loop. It is a non-isothermal loop. The test section of the loop is approximately 30 ft in length. Figures 21 through 23 show the high pressure loop installation at the hydrate flow test facility.

High pressure is achieved by routing the flow from the isothermal/non-isothermal loop to a boosting compressor. The compressor raises the pressure of this test section up to approximately 3500 psia. Heat exchangers reduce the temperature prior to the flow entering the test section.

Fluid is injected upstream of the test section. Flow velocities are constrained to less than 2 ft/sec. Visualization is a challenge with this section of the test loop due to the high pressure conditions. A number of bulls-eye windows are installed at various locations on this test section to capture hydrate morphology and flow at extreme conditions.

Water and methanol are injected downstream of the compressor prior to entering into the test section. View ports are provided to monitor the condition of the fluid as a function of the flow rate, temperature, pressure, and the amount of liquid present in the flow line.
Figure 20. High pressure non-isothermal hydrate flow loop section.

Figure 21. High pressure, non-isothermal hydrate flow loop test section.
Figure 22. High pressure midstream section showing bulls-eye window with video carriage.

Figure 23. High pressure test section showing upstream bulls-eye window.
3.1.4. **Simulated Riser**

An exploratory test was run to investigate hydrate formation in risers. A small laboratory scale riser section was constructed to investigate hydrate flow and hydrate composition concepts. The riser test section that was constructed is independent of the main hydrate test sections.

The exploratory riser tests focused on evaluating how hydrate formation occurs when gas is percolated through the liquid water phase in the riser. In order to do this, a view-port spool was positioned vertically and attached to two sections of 4” pipe. The vertical pipe was filled partially with water and then gas bubbled up from the bottom of the pipe through the liquid section which viewed and video taped through the viewing port. The tests simulated hydrate bubble flow conditions. These images are provided in a later section of this report. Figure 24 provides a schematic of the riser section. It was approximately 8ft in height and 4” in diameter.

*Figure 24. Simulated riser test section schematic.*
3.1.5. Slope Flow Hydrates Test Section

In the winter of 2006 a sloping flow test section was added to the HFTF on the return from the non-isothermal test section to the vertical separator. Its purpose is to simulate hydrate mass flow that would occur in similar flow line sections on hilly inclines in a gas storage field, in particular the Greenlick, Latigo, Loreed, and many flow lines in the National Fuel system.

The sloping flow test section consists of a 30 ft² horizontal entry section followed by a 15° incline pipe test section which is also approximately 40 ft in length. The horizontal section can be filled to different liquid levels. View ports are located at the entry to the slope and exit points. Bulls eye windows and an axial flow viewing device is installed on the incline.

Temperature, pressure, and differential pressures are monitored under different gas velocity and liquid loading conditions. Shakedown and scoping flow data were initially obtained from this test section, as well as a range of tests that investigated the development of hydrate masses on the slope. As mentioned, this was known to occur in a number of storage field locations, including the Greenlick and Latigo storage fields.

The gas storage related flow data from the hydrate flow test facility show the effect of gas velocity on water and hydrate transport through the slope test section. The test section has unique flow characteristics that are important for hydrate formation, inhibitor distribution, kinetic inhibitor performance (which was being field tested) and fluid/hydrate transport and deposition testing.

Figure 24 provides an overall view of the HFTF and shows where the sloping flow test section has been installed. Figure 25 provides an image of the slope flow test section at the laboratory. Flow tests determined the effects of an incline on hydrate formation and transport. A large amount of data has been obtained on hydrate flow for this test section. Together all of the data show the influence of liquid hold-up coupled with hydrate transport up an incline section of pipe. These are the first sets gas storage field related hydrate flow data under such conditions. The data are important. Figure 31 provides some example differential data from the orifice meter and across the test section. The tests were evaluating the transport characteristics of hydrate masses on inclines. Extensive video imaging of this type of flow has been made through two spools located at the top and bottom of the test section. Editing the video files is extremely cumbersome due to the extraordinary time and amount of data — i.e. extensive manual filtering is required.
Figure 25. Hydrate flow schematic showing the location of the sloping flow test section.

Figure 26. Slope test section image.
Figure 27. Example of hydrate flow data from hydrate slope test section.

A substantial amount of raw hydrate related flow measurement data has been processed and charted. It exists in Excel flow sheets. Additional images and points for operators are needed for this section.

The flow conditions in the slope test section that were measured included up to 100% of the lower pipe section filled with water, low flow velocities (<5ft/sec), 0 to 3 wt % of MeOH + increments of MeOH to the baseline concentrations.

3.1.6. Well-bore Hydrates Test Section

In the winter of 2007 the construction of a 50 ft. 4" vertical well-bore test section began to investigate hydrate flow and blockages in gas storage well-bores. Installation and shakedown testing was completed during the winter of 2008. A schematic of the P&ID and images of the full-scale well-bore hydrate flow test unit are provided in figures of this report.
The images show a GLCC separator that is connected to the exit of the well-bore test section to remove water and hydrates prior to the recirculation of natural gas back through the main hydrate loop. It should be noted that the separator performance of the GLCC is a function of flow velocity. In the current configuration of the well-bore test section the GLCC unit is used simply as a water knock-out separator. Figures 28 and 29 show a schematic of the well-bore test section and a picture showing the well-bore entrance and exit piping and the attached GLCC.

Figure 28. Schematic of well-bore test section.
The well-bore testing requires empirically establishing the hydrate flow characteristics in the well-bore for different flow control valve configurations. The flow tests were carried out at low fluid velocities. Test data focused on the flow characteristics that are most conducive to hydrate blockages near the subsurface control valves in the well-bore.
The tests include charging the flow loop with a preset amount of water with/without hydrate inhibitor, and then flowing natural gas through the flow lines at predetermined flow velocities. Video data is obtained on the distribution of the hydrates for each test condition. Accurate flow measurement data was obtained over the test matrix.

The hydrate flow data from the slope test section produced surprising results. The hydrate plug/mass have the same morphological characteristics as typical hydrate plugs found in gas storage field flow lines.

The flow results are a major accomplishment and are expected to be a very useful finding from this project. Duplication tests of the recent findings are being planned.

Figure 29 provides a good example of the type of hydrate masses that are present both in gas storage field flow lines and the ones produced at CEESI in the hydrate flow loop in the high pressure test section, in the slope flow test section and in the well-bore test section. Each section has a slight morphological variation associated with it. The variation depends on the hydrate flow dynamics associated with the particular test section. The mass below was obtained from the high pressure test section.

Figure 30. Example of the morphology of storage field hydrate mass.
A substantial amount of raw hydrate related flow measurement data has been processed and charted. It exists in Excel flow sheets. Additional images and points for operators are needed for this section. In general the tests were run at flow velocities of less than 10 ft./sec, pressures of approximately 900 psig, and temperatures of approximately 46 °F. These conditions were optimal for hydrate formation, flow and the control testing.

4. Hydrate Formation, Transport and Blockage Development

4.1. Hydrate Formation at Equilibrium Conditions

A significant amount of hydrate behavior in the gas storage field is due to the basic chemistry of natural gas hydrates. A practical overview of hydrate chemistry is provided here as an introduction.

The goal of this section is to show how hydrate chemistry impacts hydrate problems in the gas storage field. The link between the chemistry and the field is made through the impact the chemistry has on the hydrate temperature — pressure — composition formation and decomposition phase diagrams. It is important to keep in mind that although the chemistry aspect of gas hydrates is very important, it is only part of the means to control hydrates in gas storage fields.

The chemistry cannot address the flow/fluid dynamic aspects of hydrate behavior in flow lines. The fluid dynamic elements of gas hydrates are very complex. It includes water and hydrate transport, hydrate deposition, hydrate agglomeration and transport under flowing conditions, flow constriction development, hydrate blockage development, and hydrate remediation. The next section in the report addresses the flow dynamics at storage field conditions.

Many hydrate chemistry topics are not covered here. The reader who is interested in a more detail description of experimental and theoretical hydrate chemistry is referred to many excellent references in the hydrate literature on the chemistry of gas hydrates. That material is not repeated in this report.

4.1.1. Hydrate Chemistry

The physical chemical behavior of hydrates is a key component to understanding water and hydrate management and control options. It provides the foundation for
proactive management of hydrates and helps facilitate minimizing capital and operational costs caused by water and hydrates in flow lines.

First, a qualitative description of hydrate chemistry is provided. The qualitative description is coupled to a quantitatively storage field operating examples using natural gas samples. The coupling occurs through the hydrate phase behavior of the key components of natural gas. This approach illustrates the qualitative and quantitative impact individual natural gas components have on the temperature and pressure stability of hydrate crystalline structures.

It is extended to actual natural gas mixture compositions of common natural gas mixtures found in gas pipelines and gas storage fields. The multi-component mixtures are overlaid on storage field operating temperature and pressure conditions. This is then used to identify hydrate operating risk zones that are based on the equilibrium thermodynamic behavior of gas hydrates.

The hydrate phase diagram is the initial basis for making many operational decisions in the field regarding gas hydrate control. It identifies the approximate temperature, pressure and composition conditions under which natural gas hydrate crystals will form or decompose. It is critically important for identifying the equilibrium operating conditions for hydrate formation, hydrate decomposition, and hydrate inhibition.

Natural gas hydrates are solid, ice-like crystalline compounds that form when the lighter constituents of natural gas and gas condensate liquids combine with water at the appropriate temperature and pressure condition. Although hydrates have an ice-like appearance they have a different physical structure than ice. Water molecules create a dynamic molecular level cage-like framework around dissolved or trapped natural gas molecules. The dissolved gas molecules of natural gas and gas condensates fit inside of the water cages to form a gas hydrate crystal. Different size gas molecules fit into different size water cages.

There is a relationship between the size of the dissolved gas molecule, the size of the water cage, the occupancy of the cages (degree of occupancy), and the stability of the hydrate crystal structure. The stability of the crystal structure is driven by the extent of the occupation or saturation of the water cages by the gas molecules. The stability of the hydrate structure is determined by the overall gas composition, temperature, pressure, and time.

Hydrates occur in two common crystalline forms. The composition of the gas phase determines the hydrate crystalline form. The forms are distinguished by the crystalline cage structure that contains the dissolved gas molecule. The hydrate crystalline structure affects the temperature and pressure conditions at which the hydrate crystals form.

The two common forms are Structure I hydrate (Type I) and Structure II hydrate (Type II). Natural gas Structure I hydrate will form at lower temperatures and higher
pressures. Natural gas Structure II hydrate will form at higher temperatures and lower pressures. Both Structure I and Structure II hydrates may be found in natural gas storage fields. Another crystalline form is known to exist. This is called Structure H. It can form when heavier hydrocarbon components are present. Structure H is interesting, however, it is less relevant than Structure I and Structure II hydrates for gas storage applications.

Molecular level water cages are the conceptual building blocks of a gas hydrate crystal. The basic building blocks can be considered to be formed from hydrate water cages that consist of different numbers of water molecules. Under the right operating conditions of temperature, pressure and gas composition, the water molecules will organize themselves into crystalline (frozen) building blocks that are somewhat similar in shape to molecular size soccer balls. Gas molecules are trapped or constrained in the middle of the molecular size balls (cages). The vertices that create the shape of the ball or cages are stabilize water molecules that are “frozen” in place. Many hydrate building blocks must come together to form a hydrate crystal. Different size water cages are required to trap different size gas molecules. The differences in the cage sizes leads to different stable hydrate crystalline structures.

The diameters of the molecular water cages range from approximately 3.5 angstroms to approximately 7 angstroms (1 angstrom equals 1x10^-10 m). The diameter of the water cage determines which natural gas components can fit into the hydrate cage. The natural gas components that can fit into water cages of this size range include methane, ethane, propane, butanes, carbon dioxide, nitrogen and hydrogen sulfide. Methane is approximately 4.5 angstroms in size where iso-butane is about 6.5 angstroms. Methane, carbon dioxide, nitrogen, and hydrogen sulfide will fit into a small water cage. Ethane, propane and iso-butane can only fit into the large size water cage.

Water molecules form hydrate crystalline cages because of the physical geometry the water molecule, i.e. tetrahedral shape, and its hydrogen bonding capabilities. The hydrogen bond is the glue that helps to stabilize a hydrate at conditions that are far above the freezing point of water. Hydrogen bonds are formed through the free electron pairs on one water molecule being electrostatically attracted to the positively charged hydrogen atoms on another water molecule. The water molecules that make up the hydrate cage are linked together through a hydrogen-bonded network. The hydrogen bounded network is energetically stabilized by the dissolved gas molecules and the other hydrogen bonded water molecules.

The bonds that hold the hydrate crystal in place are relatively weak bonds. This is because hydrogen bonds have weaker bonding energies than covalently bonded chemical species. This means that hydrogen bonds require less energy to stabilize and destabilize then covalently bonded substances. Hydrate crystal cage stabilization is the basis for hydrate formation, decomposition and inhibition options.
Figure 25 shows the details of the basic hydrate crystalline structures hydrate structure I, structure II and structure H at the molecular level.

Figure 31. Hydrate crystalline structures for Structure I, Structure II, Structure H.

Gas composition and the flow line operating conditions determine the hydrate crystal structure that forms. Typically it is the amount of the largest molecule in the gas that determines which crystal structure will form. As a practical matter a relatively small amount of propane in the gas stream will cause structure II to form. A third crystalline form, called Structure H, is also possible but less common. Structure H forms with larger hydrocarbon molecules including butanes and some aromatic compounds.

The crystalline hydrate phase contains a high concentration of methane. In fact, methane's concentration is significantly more concentrated in the hydrate phase than in the gas phase at the same pressure condition.

The hydrate phase supports a surprising concentration of natural gas components, i.e. up to approximately one-third of the liquid density of pure methane. It is this concentration of hydrates in the hydrate phase that is the physio-chemical basis for the high pressure gas release that is caused by rapid heating of natural gas hydrates. It is an important point about hydrate behavior that should be remembered for safety purposes when heating and decomposing gas hydrates.
Hydrate crystals may form at the contact surface between the gas phase and the liquid phases, i.e. the gas-liquid interface. They may also form at a liquid-liquid interface such as the contact surface between the liquid water phase and a liquid condensate phase.

In gas storage fields, the liquid water phase is present as free liquid or liquid water that has condensed from the water saturated gas phase. Dissolved natural gas molecules at the gas/liquid interface are trapped in water cages. The gas molecules stabilize nascent hydrate crystals and facilitate the growth of more hydrate cages.

Once hydrate formation is initiated, gas molecules are drawn from the gas phase into the liquid water phase. In other words, gas hydrates act as molecular-level sponge that draws natural gas components from the gas phase into the hydrate crystalline (solid) phase. In theory hydrate crystal formation will consume all of the free water. In practice this requires the renewal of the gas-liquid surface area through a substantial amount of gas phase fluid mixing and turbulence through mixing with the liquid phase.

Under the right operating conditions the nascent crystals will grow and agglomerate into a hydrate masses. If gas is shut-in in the flow lines with little or no mixing, the hydrate mass will grow and form a hydrate crystalline film or hydrate skin over the surface of any free water in the flow line. The stagnant hydrate film substantially reduces the conversion rate of water to hydrate in the flow line. Mass transfer of the gas components through the hydrate film limits the conversion of liquid water to hydrate.

Hydrate masses accumulate on the surface of free liquid water or on the liquid that has condensed on the pipe wall. Depending upon the flow rate conditions, the hydrates may be transported by the gas flow to down stream locations.

Hydrate forming conditions are common in both surface and subsurface storage field flow lines and equipment for a significant portion of the gas storage withdrawal and operating season in many regions of the U.S. and elsewhere. Under such conditions hydrate masses will accumulate at rough surface locations, on the pipe wall, on protrusions on pipe walls, in instrument lines, at orifice plates, in elbows and on other in-stream equipment. Flow is severely constricted after sufficient quantities of hydrates and liquid water is held up in the flow lines.

Hydrate equilibrium curves relate the basic hydrate chemistry crystalline formation and decomposition behavior to estimates of the temperature, pressure and composition conditions. Altering the temperature, pressure and/or composition alters the stability of the hydrate cage. The changes are reflected in the hydrate phase diagram for different natural gas compositions. Hydrate phase diagrams for a number of common natural gas storage field gas mixtures is discussed in a later section.

Controlling gas hydrates using equilibrium methods generally means creating an operating condition via mechanical, thermal or chemical means that disrupts the hydrogen-bonding network of water molecules. Disrupting the network prevents water molecules from initiating and/or sustaining hydrate crystal formation and growth. The
disruption of the hydrogen bonded network may be accomplished through temperature, pressure, or chemical control of the liquid water phase.

Methanol is an effective inhibitor because it disrupts hydrate cage formation by competing with the water molecules for hydrogen bonds. This shifts the hydrate formation phase diagram to lower temperatures.

4.1.2. Hydrate Phase Diagrams

The principal equilibrium considerations for hydrate formation are the:
- Temperature
- Pressure
- Gas composition
- Gas saturation condition

The hydrate phase diagram identifies the temperature, pressure and gas composition conditions at which hydrate forming gases and water will form hydrate crystals. The diagram is determined by the gas composition. Gas compositions vary between different gas storage fields due to the gas pipeline source compositions that supply the storage fields. As discussed in the previous section, two types of hydrate crystals may be found, Structure I hydrate and Structure II hydrate. The type of hydrate crystalline structure determines the characteristics of the hydrate phase boundary. A wide variety of storage field hydrate related phase diagrams for Greenlick, Latigo, Loreed, and other locations can be found in the appendix of this report as well as general ones in this section.

Hydrate phase boundaries can be estimated based on thermodynamic equilibrium considerations. Hydrate thermodynamic models are mathematical correlations that are used to predict hydrate formation conditions. There are basically two types of models, 1) models based on molecular theory and 2) empirical correlations based on experimental hydrate phase equilibrium data.

Hydrate phase equilibrium data are obtained in many specialized laboratories that are dedicated to hydrate physio-chemical measurements including the determination of hydrate phase boundaries. The laboratory at GTI was used during this project to measure hydrate phase boundaries for the CEESI test facility gas mixture.

Hydrate thermodynamic models may be used to predict the hydrate phase diagrams for both pure and multi-component gas mixtures. The thermodynamic models, and the underlying data used to correlate and predict hydrate behavior, are not exact. The hydrate phase diagrams that are derived from the models are not exact. Nevertheless, the models provide a guide to the approximate temperature, pressure and composition conditions gas hydrates will form and decompose in flow lines. A good discussion of hydrate prediction methods can be found in the GPSA Engineering Data Book, Katz and Hammerschmidt.
The thermodynamic phase diagram is used only as a guide to help supporthydrate control methods. It does not provide a complete picture of the physical behavior of hydrates in flow lines since it cannot capture the fluid dynamic aspects of hydrate transport and blockage development. The hydrate phase diagram does not identify the time that is required for hydrate formation in real flow lines, nor does it identify the extent of hydrate formation, nor the location of hydrate masses in the flow line.

In addition to thermodynamic constraints, hydrate formation and decomposition are mass transfer limited processes. The time required to produce a significant quantity of hydrate depends on the extent of the mixing of the gas and liquid phases, i.e. the interfacial surface area that is generated in the mixing process. These depends on the unique characteristics of two and three phase flow.

Natural gas pure components and natural gas mixtures are a subset of the gas types that form gas hydrates. Selected natural gas components and related fluid mixtures help to provide approximate temperature-pressure boundaries on the type of operating conditions at which hydrates form in gas storage fields. The phase boundary conditions can be used to provide an operational range where hydrate crystals will form or decompose in the flow lines.

In the next section pure fluid gases, e.g. methane, nitrogen, propane, are used to provide bounds for the hydrate phase diagram relative to the major chemical components in a gas mixtures. Following the pure fluids, binary mixtures of gases, e.g. methane with propane, methane with nitrogen, are illustrate the impact of a given component in a mixture on the phase diagram. Lastly, representative natural gas mixtures, e.g. the compositions that is obtained from the storage field gas chromatograph can be used to provide an estimate of the actual behavior of a real natural gas relative to representative gases.

Laboratory experimental data vary relative to calculated values due to experimental uncertainty and modeling uncertainty. Six gases are used in this report to calculate hydrate phase diagrams. The gases are: 1) pure methane, 2) binary methane/propane blend, 3) Gulf Coast natural gas mixture, 4) Amarillo natural gas mixture, 5) Latigo natural gas mixture.

Table 1 contains the compositions for three natural gas mixtures. It shows a high methane content Gulf Coast gas, and two intermediate methane content gas mixtures, an Amarillo gas and Latigo gas mixture. In addition to having differing amounts of methane, the mixtures reflect the variations in the amount of ethane, nitrogen, carbon dioxide and propane on the hydrate phase diagram.
Table 1. Nominal compositions for representative storage field mixtures.

<table>
<thead>
<tr>
<th>Gas Component</th>
<th>Natural Gas Composition (Mole Percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gulf Coast Gas</td>
</tr>
<tr>
<td>methane</td>
<td>96.52</td>
</tr>
<tr>
<td>ethane</td>
<td>1.82</td>
</tr>
<tr>
<td>propane</td>
<td>0.46</td>
</tr>
<tr>
<td>iso-butane</td>
<td>0.10</td>
</tr>
<tr>
<td>normal butane</td>
<td>0.10</td>
</tr>
<tr>
<td>iso-pentane</td>
<td>0.05</td>
</tr>
<tr>
<td>normal pentane</td>
<td>0.03</td>
</tr>
<tr>
<td>hexane</td>
<td>0.07</td>
</tr>
<tr>
<td>carbon dioxide</td>
<td>0.60</td>
</tr>
<tr>
<td>nitrogen</td>
<td>0.26</td>
</tr>
</tbody>
</table>

The hydrate phase diagram was estimated for pure methane, two binary blends of methane and propane, and three natural gas mixtures including the gas mixture from the Latigo storage field.

Table 2 compares the equilibrium temperature and pressure conditions for different gas types over a range of storage field operating conditions. It shows the impact of the composition on the formation conditions as the gas is changed from a pure methane, a binary mixture of methane and propane, and then actual natural gas mixtures.

At constant pressure and relatively high pressure conditions, the total variation in the range of formation temperatures for all the gases is generally less than 10 °F. At low pressure conditions the variation approaches 25 °F.

The variation in pressure at constant temperature shows significant variation among the different gas types. Methane at 66 °F will form hydrates at 3000 psia, a methane(97)/propane(3) blend at 66 °F will form hydrates at 1500 psia, the Latigo gas mixture at 66 °F will form hydrates at 1750 psia.

The table shows the impact different gas compositions have on the temperature and pressure at which hydrates form.
Table 2. Estimated hydrate formation temperature at a given pressure condition for six different gas types for gas storage fields.

<table>
<thead>
<tr>
<th>Pressure</th>
<th>Methane (97) / Propane(3)</th>
<th>Methane (95) / Propane(5)</th>
<th>Gulf Coast Gas Mixture</th>
<th>Amarillo Gas Mixture</th>
<th>Latigo Gas Mixture</th>
</tr>
</thead>
<tbody>
<tr>
<td>3000</td>
<td>66</td>
<td>72</td>
<td>74</td>
<td>72</td>
<td>68</td>
</tr>
<tr>
<td>2750</td>
<td>65</td>
<td>71</td>
<td>73</td>
<td>71</td>
<td>67</td>
</tr>
<tr>
<td>2500</td>
<td>63</td>
<td>70</td>
<td>72</td>
<td>70</td>
<td>66</td>
</tr>
<tr>
<td>2250</td>
<td>62</td>
<td>69</td>
<td>72</td>
<td>68</td>
<td>64</td>
</tr>
<tr>
<td>2000</td>
<td>60</td>
<td>68</td>
<td>71</td>
<td>67</td>
<td>62</td>
</tr>
<tr>
<td>1750</td>
<td>58</td>
<td>67</td>
<td>70</td>
<td>65</td>
<td>60</td>
</tr>
<tr>
<td>1500</td>
<td>56</td>
<td>66</td>
<td>68</td>
<td>62</td>
<td>58</td>
</tr>
<tr>
<td>1250</td>
<td>53</td>
<td>64</td>
<td>67</td>
<td>60</td>
<td>55</td>
</tr>
<tr>
<td>1000</td>
<td>50</td>
<td>61</td>
<td>64</td>
<td>56</td>
<td>51</td>
</tr>
<tr>
<td>900</td>
<td>48</td>
<td>60</td>
<td>63</td>
<td>55</td>
<td>50</td>
</tr>
<tr>
<td>800</td>
<td>46</td>
<td>59</td>
<td>62</td>
<td>53</td>
<td>47</td>
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<tr>
<td>700</td>
<td>44</td>
<td>57</td>
<td>60</td>
<td>51</td>
<td>45</td>
</tr>
<tr>
<td>600</td>
<td>41</td>
<td>55</td>
<td>58</td>
<td>49</td>
<td>42</td>
</tr>
<tr>
<td>500</td>
<td>38</td>
<td>52</td>
<td>56</td>
<td>46</td>
<td>39</td>
</tr>
<tr>
<td>400</td>
<td>34</td>
<td>49</td>
<td>52</td>
<td>43</td>
<td>35</td>
</tr>
<tr>
<td>300</td>
<td>22</td>
<td>45</td>
<td>48</td>
<td>38</td>
<td>25</td>
</tr>
</tbody>
</table>

4.1.3. Pure Component (Methane) Hydrate P-T Behavior

Methane is the dominant component in natural gas mixtures. A familiarity with the methane hydrate formation curve provides a practical basis for a basic understanding of natural gas hydrate formation conditions.

As previously noted, the hydrate phase diagram depends on the gas composition. The gas composition and operating conditions determine the type of hydrate crystal that forms, i.e., Structure I or Structure II. The conditions for hydrate formation differ between the two types. Methane forms Structure I hydrate. Figure 26 is the hydrate formation phase diagram for pure methane.
Figure 32. Hydrate equilibrium P-T curve for pure methane.

If a gas storage system contains pure methane, the operating region to the right or below the methane hydrate equilibrium curve in figure 27 will not form hydrates. The operating region to the left of the hydrate equilibrium curve will form methane hydrates. The methane hydrate formation curve may be considered as a lower bound for hydrate formation for real natural gas mixtures that are present in a natural gas storage field. In other words, hydrate formation in a gas storage field is a certainty when water is present at storage field operating conditions that are to the left of the methane hydrate phase formation curve.

The phase diagram and hydrate formation data table illustrate the practical difference for a gas storage field between Structure I and Structure II hydrate structures. The conditions for formation are listed in Table 2. The diagrams and table may be used as a guide. It should be emphasized that the phase diagram is determined by the specific gas composition that is in the storage field location and flow lines. The phase diagrams that are provided in this report are intended only as an approximate guide.

Table 2 shows that at a given high pressure condition the difference in the temperature of formation between methane and the gas mixtures highest hydrate formation temperature is approximately ten degrees. Similarly, for a given temperature, the difference in the pressure of formation between methane and the gas mixtures varies substantially. This reflects changes in the stability of the hydrate crystalline structure as a function of
composition. Figure 27 provides the hydrate formation curve for pure methane with the hydrate operating risk zones.

Figure 33. Hydrate equilibrium P-T curve for pure methane illustrating operating risk zones for a pure methane system.

Hydrates that are formed from natural gas mixtures behave differently than pure methane hydrates. Unfortunately the other components found in natural gases, i.e. propane, carbon-dioxide, etc. shift the hydrate formation and decomposition conditions to a higher operating temperature region. This increases the operational time when storage field gases are in the hydrate formation zone.

The chemical structure of the additional components in the gas stream help to further stabilize the hydrate crystalline structure. The concentration of those components determines the crystalline structure, as well as the pressure and temperature shift. They increase the operating risks associated with the formation of gas hydrates in the flow lines.

Below a comparison of methane’s hydrate curve is made to a few representative natural gas mixtures and to a storage field natural gas. The comparisons illustrate the differences that occur in the hydrate formation region due to different storage field gas types. The first comparison is made to a binary mixture of methane and propane. This illustrates the type of behavior that may occur if LNG gas blends enter storage fields. The second group is with three common natural gas mixtures that exhibit a range of hydrate formation phase behavior.

4.1.4. Binary Mixture (Methane-Propane) Hydrate P-T Behavior
Two representative binary mixtures of methane with propane are used to show the impact of a relatively small amount of propane has on the hydrate formation curve of pure methane.

The three representative natural gas mixtures have significantly less propane in the natural gas mixture than in the binary mixture.

Figure 28 and figure 29 are binary mixtures of methane and propane. They illustrate that a relatively small concentration of propane in the gas stream will cause a significant shift in the hydrate formation conditions and crystal structure from Structure I for pure methane to Structure II for methane/propane blends.

Figure 28 and figure 29 show the hydrate formation curve for a 97/3 and 95/5 mole percent blend of methane with propane. Table 2 lists the formation conditions for these methane/propane binary blends. The curves show somewhat similar characteristics, however the data table indicates substantial numerical differences between the estimated formation and decomposition conditions of the blends relative to pure methane.

Figure 34. Hydrate equilibrium P-T curve for a methane (97)/propane(3) mixture.

The binary mixture of methane and propane forms a Structure II hydrate. The Structure II hydrate is more stable than pure methane. This results in a shift in the hydrate phase formation curve to higher temperature and lower pressure conditions. Hence the quantity of propane molecules in the gas stream substantially impacts the operating conditions at which natural gas hydrates will form in the flow-lines of a gas storage facility.
4.1.5. **Multi-component (Storage Field Natural Gas) Hydrate P-T Behavior**

Table 2 listed the composition for a representative Gulf Coast type quality gas mixture.

The methane content of this gas mixture exceeds 95 percent. This gas is a common gas composition that is found in the U.S. pipeline network. It is used here for illustrative purposes only. It is used to demonstrate how pipeline quality gas compositions help to establish the hydrate formation conditions that occur in gas storage reservoirs.

The Gulf Coast gas mixture has a very small amount of propane in the mixture, i.e., less than one percent. The amount of propane is not sufficient enough to change the hydrate crystal structure from Structure I to Structure II. Figure 30 provides the hydrate equilibrium curve for the Gulf Coast Natural gas mixture.
The hydrate phase diagram for the Gulf Coast is contrasted with the phase diagram for a lower methane content, higher ethane and propane content Amarillo gas mixture.

Table 1 lists the compositions for a representative Amarillo type quality gas mixture. The mixture is an intermediate methane content natural gas mixture. The methane content is approximately 90 percent. This gas mixture is also a common gas composition in the U.S. gas transmission pipeline network.

Figure 31 is the hydrate phase diagram for a Amarillo type natural gas mixture. In this case this gas mixture will form both Structure I and Structure II hydrate crystals depending on the operating temperature and pressure conditions.

Figure 36. Hydrate equilibrium P-T curve for a Gulf Coast Natural Gas Mixture.

Figure 37. Hydrate equilibrium P-T curve for a Amarillo Natural Gas Mixture.
Table 2 provides a gas composition from the Latigo Gas Storage Field. The Latigo storage field composition has similar gas characteristics to the Amarillo type quality gas mixture in Table 2, with the exception of nitrogen and carbon dioxide content. The methane concentration is very similar to the Amarillo gas composition while ethane is slightly higher and propane is slightly less than the Amarillo gas composition.

Figure 32 combines all of the previous diagrams into a single plot. It compares the hydrate format curves for the six gas types in order to clearly illustrate hydrate formation trends as a function of composition. It further illustrates the range of hydrate formation and decomposition temperature, pressure conditions that should be considered in gas storage field operations.

Figure 38. Comparison of hydrate formation and decomposition conditions for six different gas types.
Figure 32 illustrates the difference between Structure I hydrate formers (methane) and Structure II hydrate formers (e.g. methane-propane). The hydrate phase diagrams show a progressive shift to high temperatures and lower operating pressures as components are added to the mixture that help to stabilize structure II hydrate. Methane content decreases somewhat from left to right while the propane, ethane and carbon dioxide content increase. The hydrate phase boundary for common natural gas storage field mixtures occur between the two extremes.

Figure 32 also shows the range of temperature and pressure variation in hydrate formation for different natural gas and synthetic gas mixtures. The data indicate a hydrate formation and decomposition temperature region that differs approximately ten to twenty degrees depending upon the pressure condition. This range also reflects differences between the components of natural gas in the gas mixture and their impact on hydrate formation as a function of temperature and pressure.

Variations in the derivative of the pressure-temperature curve determine the pressure changes that occur between the gas mixtures at constant temperature. Errors in the predicted pressure increase as the slope of the curve increases at a given temperature. The pressure difference between the different natural gas types is significant.

4.1.6. Ice Formation and Hydrates

Lastly, another equilibrium consideration in addition to hydrate formation is the conversion of free or condensed water to ice in the flow lines. Although this study focused primarily on gas hydrates, however, recent imaging data from the hydrate flow loop clearly shows the presence of ice, see figure 33. The image shows what appears to be ice crystals in the presence of hydrate crystals in the background. Hence, in addition to
hydrate equilibrium considerations, flow lines that are operating below the freezing point of water, i.e. 32°F, will also have ice present.

Figure 39. Ice crystals on the CEESI hydrate test facility flow line view port window.

4.1.7. Hydrate Inhibitor Chemistry

As discussed above, gas hydrate cages consist of hydrogen bonded water molecules that are linked together in a network around dissolved gas molecules. The hydrogen bonded network is a framework that holds the hydrate structure together. Chemicals can destabilize the framework and inhibit hydrate formation. Many different types of hydrate control chemicals exist. Some chemicals alter the phase boundary characteristics of hydrates, others alter the sticking properties of hydrates, still others retard the crystal growth rate of hydrates. Molecules like methanol and glycols are thermodynamic inhibitors. They act by competing with water molecules for hydrogen bonds.

Thermodynamic inhibitors combine with the water phase to lower the hydrate formation temperature at a given pressure. The inhibitor must be at a concentration in solution that is sufficient to shift the hydrate formation phase boundary to meet the expected operating temperature requirements.
The effect of methanol concentration on the hydrate formation boundary is provided later in the section on Hydrate Inhibition and Control. Figure 34 provides a unique image of methanol interacting with a hydrate crystal on the view port section of the hydrate test loop.

Figure 40. Hydrate crystals on view-port window with methanol injected.

In addition to chemical thermodynamic controls, i.e. a control that shifts the phase boundary of hydrate formation, hydrates can be controlled by manipulating the crystal growth process. These chemicals can impact the rate of hydrate formation and the manner in which hydrates agglomerate or stick together in the flow lines. In general these chemicals are not used in gas storage fields because of concern about the impact of the chemicals on the field.

4.2. Hydrate Growth and Transport Under Dynamic Conditions

The following section needs to be updated with many additional research images due to the new data as well as editing those images to improve the clarity for the reader per the discussions with DOE.

4.2.1. Hydrate Formation and Growth
The previous section illustrated how the static operating conditions affect hydrate formation. The effect was shown for a range of gas types that are common gases in gas storage fields. The phase diagrams show that hydrate crystals will exist in the flow lines once the field operating temperature and pressure fall to the left of the hydrate formation curve for a given storage field gas composition. The presence of hydrate crystals does not imply that a hydrate blockage is imminent; rather it means that a new phase is present in the flow line and that the risk of blockage has increased.

In order to acquire better insight into hydrate flow processes extensive hydrate flow measurement experiments were performed in the hydrate flow facility to determine how the flow behavior impacts hydrate formation, transport and blockage development. This section of the report provides data from the hydrate flow facility that addresses the formation, distribution and condition of hydrates at low flow rates found in gas storage fields. It shows how hydrates actually form, move, and develop blockages in storage field flow lines.

The data show that the formation and condition of the hydrate phase in the flow line depends on the presence and location of water in the flow lines. Hydrate flow test facility video images show that hydrates form as a hydrate film on the surface of free liquid that is stagnant or nearly stagnant in the pipe. Hydrates also form on the pipe wall through the condensation of water from the vapor phase and subsequent growth on hydrate crystals on the condensed droplets.

Methane hydrate is approximately ninety percent of the density of water or about fifty-seven lb/ft³. A natural gas mixture hydrate that is predominately methane will have a density that is approximately the density of methane hydrate.

Hydrate particles and films are easily transported in both the gas and liquid phases. The mode of hydrate transport depends on the gas and free liquid velocity in the flow lines, and on the distribution of the hydrate in the liquid phase. Hydrates freely float on liquid water in the flow lines. Hydrates are easily blown down the flow lines. They grow in films of the surface of water. The hydrate films are easily broken up by the gas flow. Once broken up they begin to aggregate into hydrate masses. The distribution of the hydrate masses in the flow lines depends on the gas flow rate, the design of the system, and the operational dynamics.

Once formed, the transport, deposition and distribution of the hydrate phase depends upon the interaction between the gas flow, free liquid water, condensing water and the solid hydrate phase. This type of flow is very complex and for practical purposes must be observed.

Fluid flow regimes are typically used to characterize simultaneous gas and liquid flow. In general these regimes have not been applied to the gas / liquid / hydrate systems found in gas storage fields. Extensive systematic experimental studies have not been made in the open literature on the behavior of flow regimes with gas hydrates present over a range of
flowrates. This report provides unique images of hydrates under operating temperature, pressure and different flow regime conditions prevalent in gas storage fields.

The flow regimes are dependent on the gas velocity and the relative mass of the gas and mass of the liquid stream. Hydrates may be present and distributed in many forms in the flow lines. Hydrates will form and flow under all flow regime conditions. Experimental data on hydrate formation under different flow regimes at a range of gas velocities is very limited and needs to be expanded substantially. The flow regime depends on the gas flow rate and the liquid hold-up. In general, the flow regime will impact the manner, rate and location where hydrates formation occurs, how flow constrictions and blockages develop, and how hydrates get distributed throughout the system.

Figure 4 provided the operating conditions for the CEESI Hydrate Flow Test Facility. The conditions include non-iosthermal (surface), iso-thermal (subsurface), and high pressure operating conditions. The test fluids include water saturated natural gas, saturated natural gas, saturated natural gas with free liquid water, and mixtures with methanol. Hydrate crystals form at the contact surface between the gas phase and the liquid phases, i.e. the gas-liquid interface. They may also form at a liquid-liquid interface such as the contact surface between the liquid water phase and a liquid condensate phase. Both were observed during the flow testing.

In gas storage fields, the liquid water phase is present as free liquid and/or liquid water that has condensed from the water saturated gas phase. Once inside the hydrate phase boundary natural gas molecules that are at the gas/liquid interface or dissolved in the water phase are trapped in water cages. The trapped gas molecules stabilize the cages and form nascent hydrate crystals. The stable crystals facilitate the growth of more hydrate cages.

After hydrate formation is initiated, gas molecules are drawn from the gas phase to the hydrate/liquid water interface where additional hydrate growth occurs. In other words, gas hydrates act as a molecular-level sponge that draws natural gas components from the gas phase into the hydrate crystalline (solid) phase. With an excess of natural gas present, in theory hydrate crystal formation will continue until all of the free water is consumed. In practice this requires the renewal of the gas-liquid surface area through a substantial amount of gas phase fluid mixing and turbulence through mixing with the liquid phase, in addition it requires time.

Small hydrate crystals grow and agglomerate into larger hydrate masses. Video images from the hydrate flow test facility have captured this process. When gas is shut-in in the flow lines, with little or no mixing, the hydrate mass will grow and form a solid film or crust over any free water that has settled in the flow line. The stagnant hydrate film substantially reduces the mass transfer rate of the gas and the subsequent conversion of water to hydrate crystals in the flow line.

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Hydrate masses accumulate on the surface of any free liquid water or on the liquid drops adhering to pipe walls. Depending upon the flow rate conditions, the hydrates may be transported by the gas flow to downstream locations.

Hydrate forming conditions are common in both surface and subsurface storage field flow lines and equipment for a significant portion of the gas storage withdrawal and operating season in many regions of the U.S. and elsewhere. Under such conditions hydrate masses will accumulate at rough surface locations, on the pipe wall, on protrusions on pipe walls, in instrument lines, at orifice plates, in elbows and on other in-stream equipment. Flow is severely constricted after sufficient quantities of hydrates and liquid water is held up in the flow lines.

Below figure 35 and figure 36 provide two high resolution images of microscopic hydrate crystals attached to a pipe wall at the CEESI hydrate flow test facility. The test conditions are 900 psia and 45 °F.

Figure 41. High magnification microscopic image of hydrate crystal. Image is from view port wall at the hydrate flow test facility illustrating hydrate surface structures.

Figure 42. Low magnification microscopic image of natural gas hydrate crystal in water on pipe wall at CEESI test facility illustrating hydrate surface interface structures with water phase.
The interfacial edges illustrate that hydrates have a high surface area. The large surface area is the region that supports rapid hydrate crystal growth. It is also the region responsible for the agglomeration of hydrate crystals into larger hydrate masses.

The irregular interface also illustrates how small hydrate crystal particles stick together and entrap other fluids at the boundary. It shows that fluids, including water, condensates, and small particulates are easily trapped in these regions as hydrate crystal masses aggregate and increases in size through mixing.

The operating conditions determine the phase and crystals that will form in the flow lines. When operating conditions are at or fall below 32 °F, ice crystals will form. Both ice crystals and hydrate crystals will be present in the flow line below 32 °F. This is a common condition for gas storage field flow-lines, flow meters, expansion devices and other surface equipment that is exposed to low ambient temperatures or significant cooling due to Joule-Thomson expansion and cooling. It is difficult to distinguish the hydrate phase from the ice phase in the field or at the hydrate test facility flow line. High resolution images where obtained in order to confirm that both hydrate and ice crystalline phases were present when test conditions went below 32 °F. Figure 37 shows the structure of ice as seen through the view port window.

Figure 43. High magnification image of ice in flow line.
Figure 38 was obtained at 900 psia and less than 32 °F in the hydrate test facilities with natural gas under shut-in conditions. The image is taken through the view port into the flow line. The fluid was at shut-in conditions. The set-up for this experiment is shown in figures 10 and 11.

Ice crystals are visible in the foreground. It is difficult to identify the crystals in the background of the image however their irregular shape suggest that they are hydrate crystals.

Figure 44. Ice and hydrates on the CEESI hydrate test facility flow line view port window.
4.2.2. **Hydrate Growth in a Static Fluid in Flow Lines**

Figure 39 is a cross-sectional view of a large hydrate mass. The image is looking into a four-inch flow line that is operating at similar temperature, pressure, and flow rate operating conditions as those in many gas storage fields. The mass is seen through the high pressure glass view port at the CEESI hydrate test facility, i.e. from the equipment shown in figures 6 and 7. The flow line was operating at 900 psia and 45 °F.

This is the same type of hydrate mass that would be expected to be present in gas storage field flow lines when free water is present in the flow line or when water and hydrate splashed on the walls of the pipe due to the flow.

**Figure 45. Cross sectional view of a Natural gas, water and gas hydrate in the CEESI hydrate flow test facility.**

The gas phase is in the top of the image, the hydrate phase is in the middle of the image, and the water phase is in the bottom of the image. The image is at a normal resolution.

The top portion of the image shows hydrate crystals that have splashed on the view port window. Behind the top view is the gas phase. The center portion of the image is the hydrate surface / interface. It is between the gas phase and the liquid water phase. The lower portion of the image is the water phase. The water phase has hydrate crystals circulating in it.
4.2.3. Hydrate Growth with Mixing Induced by Gas Flow

The next sequence of images was one of the first sets of images from the test facility. It provides data from the early experiments in the non-isothermal portion of the test loop. The images show that the gas flow induces mixing between the hydrate phase and liquid water phase. The sequence is seen in figure 37.1 through figure 37.4. The top of each image is the gas phase, the middle is the hydrate phase, and the low portion of the image, the water phase.

Figure 40.1 shows a pre-flow hydrate film, figure 40.2 shows the flow increasing the depth of the hydrate film, figure 40.3 shows the flow inducing turbulence in the hydrate layer and producing waves between the hydrate phase and the water phase, figure 40.4 shows the hydrate phase being mixed with some recirculation.

The flow induced mixing process has the effect of generating significantly more surface area for gas hydrates to grow.

Figure 46. Natural gas, water and gas hydrate in the CEESI hydrate flow test facility. Illustrates hydrate flow line mixing as hydrate mass washes on side of pipe wall.

As the height of liquid water in the flow changes, the hydrate film / crust increases and decreases. Free hydrate particles are observed to be circulating in the liquid phase.
4.2.4. Hydrate Growth with Gas Condensates Present in Flow Lines

In addition to hydrates forming with a single water phase in storage field flow lines, hydrates were also observed to form in the presence of gas condensate liquids. Figure 41 is similar to figure 39, only there are two liquid phases, i.e. a condensate liquid phase and the water liquid phase. A simulated gas condensate was used in this test. The simulated condensate was Stoddard solvent. Light hydrocarbon components of natural gas dissolve in the Stoddard solvent and form hydrates at the physical boundary between liquid condensate and liquid water.

The top of figure 41 is the gas phase. The hydrate phase is blocking the view into the center of the pipe. It is difficult to identify the different regions through a cross-sectional view in the view port because of the extent of hydrate formation. The center of the image in figure 6 is the condensate solvent and the bottom bright section of the image is water. Hydrates have formed between the water and condensate phase and have grown up the entire side of the viewing window. This picture shows that a small amount of condensate has a dramatic impact on the hydrate phase.

Figure 47. Natural gas, water, condensate and gas hydrate present. Hydrate mass consisting of water phase, hydrate phase, condensate phase, hydrate phase and flowing gas phase.
4.2.5. Hydrate Growth in Mist Flow Conditions

These tests were conducted to obtain data on hydrate growth from a water saturated gas stream. It is an important flow condition in the gas storage field. Mist, i.e. fog, is formed in the flow lines by water droplets condensing from the gas stream. The gas velocity carries the liquid as small droplets and distributes them on the pipe wall. This flow condition exists in production tubing, casing, surface and subsurface flow lines.

Condensing liquid creates a thin-film on the pipe wall. Once a liquid film is created hydrates will form on the pipe wall. Under shut-in conditions the liquid will pool in the bottom of the pipe and promote the formation of a hydrate film over free liquid water.

Figure 42 provides an axial view into the flow stream with condensing flow. The images were obtained from the isothermal test section, see figure 13. The view is looking upstream towards the flow. Light is reflecting off of the liquid droplets in the flow. Water is condensing in the flow line and is distributed as a fog in the gas phase. The fuzzy images on the walls are hydrates on the pipe wall.

Figure 48. Axial view of fog in the flow line.
Figure 43 shows hydrate growth on the pipe walls that formed from condensed water. The dark spot in the center of the image is looking upstream into the flow. The light is reflecting off hydrates masses that have grown from condensed water on the pipe wall.

Figure 49. Hydrate and condensing flow in the flow line

4.2.6. Hydrate Growth with Stratified – Separated

Another type of flow that occurs in the storage field is stratified-separated slug flow. This type of hydrate flow is formed from a continuous liquid phase with a hydrate film /mass over the surface of the water. Keep in mind, as long as there is water in the flow lines, and the system is inside of the hydrate phase boundary, hydrates will continue to grow regardless of the fluid dynamic condition of the flow.

The data show that as hydrate films grow in the flow stream, the hydrates aggregate into larger hydrate masses. The hydrate masses are less dense than the water and get pushed and carried by the flow to the walls of the flow line. They typically accumulate at the height of the liquid water on the walls of the pipe. This is can be seen in the cross sectional views in figures 39 and figure 40. The accumulation of hydrate masses constricts and impedes the flow.
The flow of hydrates in the flow stream is retarded or even stopped by protrusions or constrictions in the flow lines. This would include pipe joints, elbows, orifices, instrument probes, T’s, etc. Hydrate flow can transitions to slugging behavior as pressure builds behind the distribution of liquid and hydrate in the flow line.

Figure 44 shows a hydrate mass being carried downstream on liquid water. It also shows hydrate growth on the wall of the flow line. The growth on the walls will act to impede the flow of the hydrate mass.

Figure 50. Gas, free liquid and hydrate prior to an induced pressure transient.

Liquid water and hydrate masses become entrained in the gas when a pressure pulse is introduced by the operating condition, e.g. start-up conditions. This type of flow occurs under transient operating conditions during start up where high gas velocities are induced by a pressure differential in the flow line. This causes a rapid redistribution of the liquid and hydrate phase throughout the line. The pressure pulse forces the flow into an annular regime.
Figure 45 shows the distribution of hydrate and liquid that is entrained in the gas due to a pressure transient. A large hydrate mass is pushed upstream towards the viewer, hydrate particles are blown down the pipe and against the walls due to the gas velocity.

Figure 51. Hydrate/liquid slug-annular flow conditions induced by a pressure transient in the flow line.

4.2.7. **Hydrate Growth with Slug Flow Conditions**

Hydrate slug flow occurs when a hydrate mass builds up in front of a mass of liquid in a low lying section of flow line. Gas pressure builds and then expands through the hydrate/water mass before the hydrate mass hardens or ages into a full hydrate blockage. The expansion process induces liquid water/hydrates into a localized slug flow behavior, masses of hydrates will accumulate in front of the liquid water slug. Multiple hydrate masses of different aggregate densities will exist concurrently in flow lines.

Figure 46 shows the progression of a hydrate mass that was formed upstream by flow perturbations over a hydrate film. The image is a cross sectional image looking through a bulls-eye window into the flow line. It was taken in the non-isothermal section of the test.
loop, see figure 8. The hydrate mass is progressing based a bulls-eye window that is viewing the flow line. The hydrate mass is transported by the gas on a liquid film. The sequence of hydrate images begins with the leading edge of the hydrate mass in image 1, followed by the peak in image 2, 3 and then the trailing edges in images 3 and 4.

Figure 52. Cross sectional view of the progression of a hydrate mass, i.e. hydrate “berg” in the flow line.

Large hydrate masses displace water in the flow lines. Depending on flow velocity, the hydrate bergs will move push free water downstream like a wave. The differential pressure exerts a force on the hydrate mass which exerts a force on the liquid phase.

When hydrate masses or bergs are present in the flow line, they will begin to be packed into constricted regions in the flow lines. The packed hydrates creates a back pressure that is one of the signals that a hydrate blockage is being formed.

It is important to realize that multiple hydrate masses are present in the flow lines. Hydrate masses hold-up the flow of any liquid, e.g., water and/or methanol. The hold-up leads to an uneven distribution of liquid in the flow line.
4.2.8. **Hydrate Growth with Bubble Flow Conditions**

Scoping experiments were conducted at the hydrate flow test facility to investigate bubble flow conditions in a bench scale simulated tubing (riser), see figure 21. The tests apply to flow conditions were the flow line is vertical and is filled with liquid water. These conditions do not exactly mimic riser conditions in the gas storage field.

The test used a small section of vertical 4” pipe partially filled with water. Different gases, including natural gas, were bubbled through the liquid water phase. A viewing port was position vertically in order to observe the gas liquid interface in the pipe. The flow of the gas and its conversion into the hydrate phase was visually recorded.

Figure 47 provides data that was obtained under bubble flow conditions with hydrate formation. The liquid phase is has a milky appearance which is a sign of hydrates.

Hydrate bubbles rise vertically through the liquid. A frozen hydrate crust forms around the gas bubble at the liquid and gas interface. The hydrate crusted gas bubbles flow to the liquid and gas interface in the test section. The hydrate crusted gas bubbles aggregate at the surface and eventually form a cap on the gas flow.

**Figure 53. Gas bubbles and hydrates percolating through liquid water phase.**

Figure 48 shows that the bubbles promote the development of a hydrate cap over at the gas liquid interface. The hydrate cap will be cracked by the build-up of gas pressure beneath it. The cap will then reform and continues to build under these conditions until a larger stronger hydrate cap has formed that is capable of holding back the gas flow. Additional growth occurs into the liquid phase as hydrates are provided gas hydrate formers from the percolating gas bubbles.
Figure 54. Bubbles create a hydrate cap over the liquid phase.
4.3. Hydrates Transport and Blockage Development

4.3.1. Hydrates in Storage Field Flow Lines – Free Liquid

This section provides data from the hydrate flow test facility on hydrate transport and blockages in flow lines. The test includes free liquids, condensing liquids from the vapor phase, and a combination of free liquids and condensed liquid mechanisms. Among other properties, the mechanism for hydrate transport and blockage development depends on the distribution of the hydrate phase in the flow line. The following sequence of images provides axial views of the steps that create gas hydrate deposits, constrictions and blockages from free liquids in a low-velocity gas flow line. Most of the data were obtained from the isothermal test section, i.e. figures 16 and 17.

The first sequence of images begins with pristine pipe surfaces. The figures provide axial views looking upstream. The gas and liquid flow coming towards the viewer. Free water was injected into the flow line following the condenser section. The images were taken inside of the hydrate formation region shown in figure 4. The test conditions in general were approximately 45 °F and 900 psia, well inside the hydrate phase boundary. The first sequence of images illustrates how hydrates initially build up and create constrictions from free flowing liquids. Keep in mind that this mechanism is for low flow gas flow rates.

The figures provide a steady progression from free liquid water without any hydrates, to hydrate mass formation, hydrate transport, and finally to hydrate blockage development in the flow line. Figure 49 shows the initiation phase of a stratified free liquid water flowing along the bottom of the pipe (reflected light surface). The fluid and gas are in the gas hydrate formation region. Hydrates are rapidly developing on the surface of the liquid.

The view in figure 49 is upstream looking towards the gas and liquid flow. The dark center of the image is the pipe. Light is reflecting off of the walls of the pipe. The light source is on the left side of the image. The flow is towards the viewer. A temperature probe is protruding into the flow stream halfway up on the left, its reflection is on the right side of the image. The light on the bottom of the pipe is the reflection of the light source off of the surface of free water, which is flowing towards the viewer.
Figure 49 shows the initial progression of the free liquid as it flows further down the flow line. A faint hydrate curb is observed to be forming on the left and right side of the flowing liquid where the liquid is contacting the cold pipe wall. The hydrate curb or rail is clearer in the following images.

Figure 50 has the same configuration as figure 49. It shows the further development of the liquid stream and the progressive conversion of hydrates on the edges of the stream that touch the wall. The hydrates were developing rapidly in this sequence of images.
Figure 56 shows hydrates as they begin to accumulate against the pipe wall in the flow line. The accumulation against the wall looks like a "curb" of hydrates at the gas, liquid, wall boundary. Free liquid water continues to flow in the middle of the flow stream. The hydrate curb runs the length of the gas, water, pipe wall boundary. A hydrate mass is seen to be developing at the leading edge on the surface of the liquid stream. The liquid flow pushes this mass which promotes mixing and hydrate growth at the leading boundary.

Figure 51 is an important image because it not only shows the flowing stream of water with hydrates to the sides of the main flow stream, but it shows the manner in which a hydrate inhibitor such as methanol travels in the liquid phase at a low velocities in the flow stream. This image makes it clear that traditional methanol treatment will be poorly distributed in the flow lines. This is because it will pool in the bottom of the flow line and will not be distributed to all the hydrate locations.
The gas flow forces hydrates that are being transported on the surface of the water to begin to dam up against the hydrate curbs on the side of the pipe. This causes the surface hydrate film on the liquid to break up and produce large hydrate masses. It also forces the hydrate up the side of the pipe wall to create the observed hydrate curbs. We observe these images in the cross-sectional views of the flow.

This type of flow causes the upstream hydrate film to break up and begin to hydrate mass jams in the flow stream. Larger hydrate masses begin to aggregate into hydrate slugs or bergs. As more liquid enters the flow line upstream the bergs rise with the level of the water and further downstream with liquid water. Gas velocity and pressure fluctuations drive the masses into bergs. Transients cause the hydrate bergs to pack downstream.
Figure 52 shows the initiation of phase of a large hydrate mass, i.e. "hydrate berg" on a stream of liquid water in the flow line. There are two bergs in this image, one in the foreground the other in the background.

During shut-in conditions, new hydrate growth is severely restricted due to the formation of a hydrate crust over the surface of free liquid. The hydrate crust impedes the mass transfer from the gas to form new hydrate. Any liquid water that is trapped in the hydrate mass but in contact with the gas phase, will be converted to the hydrate phase.

Figure 53 shows the progression of the mass downstream and beginning to compact into the flow line.
As gas flow continues, the hydrate mass is compacted into the flow line. The compacting process pushes the free water in front of the hydrate mass. Hydrate compaction into larger masses appears to occur in a cyclical manner as pressure builds behind the mass in the test loop. This process may differ somewhat in the field. The compaction process produces back pressures and creates differential pressure fluctuations. The overall gas flow rate is reduced and the differential pressure across the hydrate mass increases.

Figure 54 shows the hydrate mass rising as liquid water gets held-up in the flow line. The hydrate mass continues to build-up over the surface of free liquid. The hydrate mass is approaching the top of the pipe.
Figure 55 is the last image in this sequence. It shows that the hydrate mass has been transported and compacted to the view window. The hydrates and underlying water has completely blocked the entire cross sectional area of the pipe. The mass is completing obstructing the view through the viewing window and beginning to create a full flow line blockage.
Figure 61. Hydrate view window completely obstructed by gas hydrates.

Figure 55 is the final image in this hydrate blockage sequence. Hydrates have completely covered the viewing window. The viewing window is located in the top one-third of the pipe.
4.3.2. Hydrates in Storage Field Flow Lines - Condensing Flow

The previous section provided data on the mechanism of hydrate transport and blockage development from a free liquid surface. This section presents data on hydrate formation and transport and blockage development in the flow line due to condensation from the gas phase.

In addition to hydrate formation on the surface of free water, natural gas transports water as water vapor in the water saturated gas phase. The manner in which the water is transport and deposited depends on the velocity of gas stream. The data obtained is for low velocity gas. At a given operating condition, the gas phase can only transport a fixed amount of water. The amount of water carried in the gas phase depends on the specific operating conditions at specific points in the flow line.

Water vapor will condense and re-vaporize depending upon the degree of saturation of the gas phase and the temperature of the field equipment in the flow lines. The amount of water in the gas phase is determined by the saturation conditions. As the gas temperature and pressure in the flow lines changes the amount of water carried by the gas phase changes.

Re-vaporization will occur when the fluid temperature is warm and the gas stream is under-saturated. The warm liquid water evaporates into the under-saturated gas stream. Condensation occurs when the gas stream contacts a pipe wall that is colder than the saturated gas stream.

The driving force for condensation and re-vaporization is the difference in temperature between the saturation temperature of the gas at a given pressure and the temperature of the wall or free liquid. As liquid drops out, the gas approaches the equilibrium water concentration amount with the flow-line wall temperature. Once it reaches this condition no additional water will condense on the pipe wall.

Figure 56 provides data on a water saturated gas phase with small water droplets in the vapor phase. The view is an axial view looking upstream into the flow. Light is being scattered off of the viewing window, off of the liquid droplets in the flow and from the wall.

Liquid droplets are condensing on the pipe wall. A hydrate film forms over the droplets. The hydrates grow as more water and gas is deposited on the condensed liquid / hydrate masses on the pipe wall.
Figure 57 provides data that shows a progressive build up of hydrate crystals on the pipe wall due to the gas phase saturated with water vapor. The view is the same as in figure 56. The operating conditions are approximately 25 °F subcooled below the saturation temperature of the gas stream.
Hydrate growth due to condensation is a slow process. In the test loop it takes days of cycling the test gas between flowing conditions and shut-in conditions to cover the interior surface of the flow line with hydrates.

Figure 58 continues this sequence of condensation images. It shows the wall surface beginning to be covered by hydrates. The figure appears to shows locations where larger hydrate masses have formed on the walls and in the bottom of the flow lines.
Figure 59 shows the hydrate growth progression on the walls after approximately one week had passed. The flow cycled between steady state flow conditions and shut-in conditions during this time period, i.e., it was discontinuous flow during this period due to test facility constraints.
Figure 65. Hydrate build-up covers the interior walls. A small hydrate mass sits in the bottom of the flow line.

Condensation and subsequent hydrate crystal formation on the pipe walls is a dynamic process. It occurs continually in gas storage field flow lines due to the water saturation condition of the gas phase. Hydrates are continually building on the walls of the pipe, melting, forming liquid pools on the bottom of the pipe, and then reforming hydrates on the surface of the liquid and side walls of the flow lines.
4.3.3. Hydrates in Storage Field Flow Lines – Condensate Liquids

When liquid hydrocarbons (condensates and oils) are present in the gas storage field formation, gas hydrate formation and transport is more complex. The condensate phase creates another liquid surface for hydrate formation. Hydrate formers from the gas phase dissolve in the condensate phase and promote hydrate formation at the condensate water interface. The data suggests that the presence of condensates adds to the hydrate formation surface area. Condensates also appear to significantly alter the character and the dynamics of hydrate formation in flow lines.

Typically the amount of produced condensate in the storage field is small relative to the amount of water that is produced. Although small, it does appear to have a relatively significant impact on hydrate formation. It is not clear how condensates with hydrates impact the flow behavior of hydrates. Studies are underway at the test facility to understand this.

The work presented below, figure 57, shows how condensates impact hydrate growth in the flow line. The view is a cross sectional view into the flow line view port. Condensate appears to increase the surface area available for hydrate formation. It also increases the concentration of hydrate formers in the condensate phase at the water-condensate boundary.

The presence of condensate induces hydrate formation at the liquid-liquid interface between water phase and the liquid hydrocarbon phase. In addition, it appears to facilitate a water/hydrate wicking mechanism which promotes hydrate growth over the condensate phase and rapidly up the interior of the pipe wall.

It has been suggested that a condensate phase may hinder the rate at which hydrates decomposition is accomplished. This was not experimentally observed in the flow laboratory. Rapid hydrate decomposition was observed through the view port when condensate was present.

Figure 60 shows the interaction of the water phase, condensate phase, and gas phase. The water phase is on the bottom of the figure, the condensate phase in the middle and the gas phase on top. Hydrates have grown between the water and condensate phase and the condensate/water/gas phase on the top of the image. The hydrate phase wicked up the pipe wall and encrusted the entire interior cavity of the pipe.

These images were taken at low flow conditions. Axial views of hydrates with condensate in the flow lines are not available at this time. Data is not available on hydrate blockage development with gas condensates in the flow lines.
Figure 66. Water phase, condensate phase and hydrate phases in hydrate test loop.
4.3.4. Hydrates in Storage Field Flow Lines – Transient Flow

The formation, transport and deposition of hydrates by free water and condensation appear to be the predominant mechanism by which gas hydrates develop flow line blockages. The data suggests that the most significant quantity of gas hydrates form at the gas and free water interface. The data presented in this section shows how operating procedures effect hydrates movement.

Turbulence induced by the gas flow at the gas liquid interface causes hydrate masses to form and grow rapidly. These conditions occur when the gas and liquid are in contact at or below the hydrate phase formation temperature and pressure condition. Both steady state and transient gas flow conditions promote gas and water mixing in flow lines to generate new surface area for hydrates to grow, agglomerate and accumulate.

Start-up conditions and operational transient conditions induce significant pressure perturbations in the flow lines. These disturbances effect all aspects of hydrate formation, growth, deposition and blockage development. In particular they effect the distribution of the hydrate phase by carrying light hydrates rapidly downstream.

Transients cause hydrate films on a static fluid to rapidly break-up. This process creates new surface area for hydrate growth to occur. Pressure perturbations change the flow regime of the fluid. A change in the flow regime causes a redistribution of the hydrate phase throughout the pipe.

Figure 61 through figure 66 provide dramatic visual data on the impact of a flow line transient on gas hydrate transport and blockage development in the flow lines. The views are axial views looking upstream into the flow.

Relatively low gas phase flow velocities are sufficient to transport hydrates downstream. The gas phase picks up hydrates from the surface of the liquid water phase and off the wall, and then rapidly transports the hydrate particles downstream in the gas phase at the velocity of the gas phase. A mobile hydrate masses can easily contribute to an existing constriction or blockage in the flow line by packing into an existing hydrate constriction and blockage. It can also initiate a new hydrate constriction.

The transient sequence in figures 58 through 63 begin with a hydrate mass in the bottom of the flow line. A pressure transient was generated that created a gas velocity of approximately 15 ft./sec. The gas flow and hydrate mass is moving towards the viewer.

Figure 58 shows the flow stream just prior to the introduction of a flow transient. The hydrate mass is lying stagnant in the flow line.
Figure 67. Axial view upstream prior to start-up / hydrate transient conditions.

Figure 62 shows the initial frames after a flow rate spike has been introduced into the flow line. Light is reflecting off hydrate masses which are being carried downstream by the gas phase. The hydrate masses are coming in the direction of the viewer.

Figure 68. Axial view – just after start-up / transient conditions – initial hydrate masses blowing downstream shortly after pressure transient.
Figure 63 shows that more hydrates are being blown downstream by the gas flow and it appears that a large mass in the middle of the image is moving towards the viewer.

Figure 69. Axial view, start-up / transient conditions – quantity of hydrate is increasing and blowing downstream in the gas stream.

Figure 64 shows the hydrate mass is being pushed by the flow and that it is coming closer to the axial viewing port. It also shows hydrates being transported in the gas flow stream.

Figure 70. Axial view, start-up / transient conditions – masses are aggregating into larger masses.
Figure 65 shows that the view window has been completely covered by the flow of hydrates being blown downstream by the pressure transient.

Figure 71. Axial view, hydrate start-up / transient conditions—hydrate masses accumulating upstream on the viewing window and blocking view.

Figure 66 is the final figure in this sequence. It shows that hydrates have completely covered the axial viewing window.

Figure 72. Axial view, hydrate start-up / transient conditions—hydrate masses completely cover the view window.
4.3.5. Hydrates Monitoring Equipment in Flow Lines

The preceding sections on hydrates in free liquids, in condensing flow, with condensates, and with transient flow show how extensive hydrate coverage is in the flow line. The flow and condensation data show that hydrates can be expected to impact the performance of monitoring probes.

Any probe or protrusion into the flow will be susceptible to hydrate deposition, or hinder the flow of hydrate masses and facilitate hydrate blockage development. The data suggest that hydrates likely contribute to the malfunctioning of flow line instruments.

Instrument lines and probes provide surfaces where hydrates can deposit or agglomerate. They also provide a mechanism for obstructing hydrate mass flow at the instrument location by snagging a hydrate mass as it moves by the probe location.

Figure 67 provides data that shows an axial view of a flow line temperature probe. The flow is in the direction towards the viewer. The temperature probe is protruding from the left side into the gas flow stream. Hydrates are growing on the wall downstream of the probe.

Figure 73. Axial view of a flow line temperature probe.
As flow is started, a hydrate mass moves into and contacts and becomes snagged on the temperature probe. At high velocity conditions, with hardened hydrate masses, the temperature probe will likely snap.

Figure 68 shows the hydrate mass snagging on the temperature probe.

Figure 68. Hydrate temperature probe constriction and blockage development.

In addition to temperature and pressure probes, flow monitoring is an important element to the field operations and to hydrate control.

Many of the previous axial views into the flow stream with hydrate present, show the challenge that is presented by monitor flow rate when the operating conditions are within the hydrate region. Experimental studies were made using ultrasonic meters, figure 9, orifice meters, and some proprietary electromagnetic flow monitoring devices.

Hydrates are easily transported through orifice meters despite the orifice meter creating a dam for liquid water. Hydrate masses are extruded through the orifice plate by the flow. The extruded hydrates help create lumps of hydrate masses downstream of the orifice. Two types of non-invasive flow measurement devices were investigated.
Clamp-on ultrasonic data was obtained in the non-isothermal section of the test loop. It relies on an ultrasonic signal path that samples a portion of the gas flow field in the flow line. When hydrates are present they block the ultrasonic signal field. This can provide an off type of signal to detect when hydrates are present in quantities that are sufficient to block the signal path. More extensive flow test data are needed for this technology in order to identify its utility and limitations in the gas storage field.

In addition to orifice and clamp-on ultrasonics data studies, an exploratory study was made of a proprietary electromagnetic flow measurement device. These data were also obtained in the non-invasive section of the test loop. The device offers unique flow data. It appears capable of identifying both the water phase and the hydrate phase. Limited flow data have been acquired for this device on gas hydrates. More systematic test data are needed to identify the utility and limitations of these devices for hydrate flow monitoring in the gas storage field.
5. Hydrate Inhibition and Control

5.1. Hydrate Inhibition Chemistry

Other than complete water removal from the gas (dehydration) and from the liquid (separation), methanol is the most effective means to control hydrates in the gas storage field. As discussed earlier, methanol prevents hydrates by competing for water's hydrogen bonds. Methanol inhibits the ability of water to form stable hydrate crystals with gas components and shifts the hydrate equilibrium curves to the left.

The phase diagram is the basis for controlling gas hydrates with methanol. In order for methanol to be effective in controlling hydrates, it must be present in the proper concentration in the water phase. The amount of methanol that is required to achieve a given level of hydrate inhibition in the flow line is a function of the operating conditions, i.e. temperature, pressure, gas composition, and the amount of liquid water present at a particular point in the flow line. This can be difficult to ascertain. These conditions depend on the particular location and can vary as a function of time, and between surface and subsurface flow lines.

The field engineer responsible for injecting methanol needs to know the maximum amount of water in the flow lines in order to determine the amount of methanol that will be required to maintain flow lines free of a hydrate blockage.

Accurate water determination in the flow lines is critical to hydrate control and optimized methanol usage. It is also important to know the amount of water in the flow lines at specific points, e.g. low points, low flow points, where water accumulates over time, in order to get the correct amount of methanol into the flow lines at those points. This must include identifying points in the flow lines where flow streams are combined and additional, uninhibited water may be present.

5.2. Hydrate Inhibition with Methanol - Phase Diagram

Methanol causes the hydrate phase equilibrium curve to shift to lower temperatures. In principle this prevents hydrate blockages at lower operating temperatures for a given pressure condition.

Figure 74 illustrates the effect different methanol concentrations have on the hydrate formation curve. This is an approximate diagram and is only intended for illustration purposes. Do not use figure 74 for gas storage field hydrate control. The gas composition used in this example is an Amarillo natural gas mixture with the composition listed in Table 1. The curves illustrate the effect on the hydrate phase boundary caused by increasing the methanol concentration in 10 wt.% increments relative to the amount of water.
Figure 75. Estimated methanol requirements vs. T-P operating conditions for an Amarillo gas mixture.

For example, to inhibit a storage field gas that is shut-in at 20 °F and 1200 psia requires at least thirty weight percent methanol to prevent hydrate formation at that condition. Storage field flow line conditions can easily approach 10 °F. At such conditions the amount of methanol required if water is present is on the order of 40 wt % of the amount of water that is present in the flow lines.

The curves in figure 69 show that for a flow line at 1500 psia, a 30 wt % solution of methanol will prevent hydrates from forming down to approximately 25 °F. A subsurface line at 1500 psia and 55 °F would require approximately 10 wt% methanol. In other words, for every 10 lbs of water in the flow at this condition, a minimum of 3 lbs of methanol is required to prevent hydrate formation down to 25 °F.

Storage field flow dynamics moves the gas and liquid between low surface temperatures, and moderate subsurface temperatures. Both conditions are inside of the hydrate phase boundary. In addition to the temperature and pressure behavior, methanol control depends on water behavior and the ability to accurately track it throughout the flow line network.

Figure 75 can be super-imposed over the P-T operating region for each gas type that may occur in the storage field to see the impact of methanol on hydrate operational risk zones,
e.g. figure 70. In general, methanol, when applied in the correct proportion, will shift the yellow zone to the left, widening the operational area and lowering the risk of hydrate formation and flow blockage problems.

Figure 76. Natural gas storage field hydrate operating zones and fluid phases that may be present in those zones.

Figure 77. Influence of composition on hydrate formation conditions for storage field and related gases.
It is important to keep in mind that water likely exists in multiple forms in the flow lines. It is present as free water, as water in the vapor phase, as water that is condensed on the pipe wall, as water in the hydrate phase, as water potentially combined with another flow stream that has some unknown concentration of methanol in it, as water trapped and if the conditions are right, as ice.

Figure 78. Minimum methanol concentrations for various operating temperatures for the Latigo and Greenlick Storage Fields
5.3. **Hydrate Inhibition – Free Water**

The next set of data, figures 71 through 75 shows the effect progressive increases in the amount of a methanol in a water stream as it flows through a hydrate mass located in the hydrate test loop view port in figure 6. The sequences begin with a fully developed hydrate mass followed by progressive amounts of methanol into a simulated drip.

The concentration of the methanol in the water solution is changed in the drip until it reaches a sufficient concentration to dissolve the hydrate phase. It should be noted that a thick film of hydrate mass remains on the side of the pipe wall as the hydrate in the water phase dissolves.

The following images provide cross-sectional views through the hydrate view port.
Figure 80. Initial hydrate mass in the view port – no methanol.

Figure 81. Hydrate mass in flow loop view port – methanol injected – hydrate cap over liquid water begins collapsing.
Figure 82. Hydrate mass – methanol injected – hydrate cap in flow stream still collapsing (dissolving)

Figure 83. Hydrate mass – methanol injected – hydrate cap appears fully dissolved
Figure 84. Hydrate mass – final image – hydrates in the center of the pipe are fully dissolved except for hydrates that remain on the pipe wall.
5.4. **Hydrate Inhibition – Condensed Water**

In addition to free water, hydrate inhibition needs to address hydrates that form by condensation.

The following sequence of images, figure 73 through figure 77 show condensed hydrates that are constricting a flow line. The view is an axial view that is looking upstream into the flow.

The test investigated hydrate removal using the typical hydrate drip injection method found in the gas storage field with a method of injecting a slug of methanol and inducing a flow transient in the flow line to improve the distribution of the methanol throughout the flow line.

Figure 76 shows the extent hydrates that have coated the interior pipe wall due to condensation prior to treating with a methanol.

**Figure 85. Pre-MEOH injection**

![Pre-MEOH injection](image)

Figure 77 shows the initiation phase of a methanol stream used to simulate a methanol drip.

**Figure 86. Methanol stream in bottom of flow line dissolving hydrates in bottom of pipe**
Comparing figures 77 and 78, the lower center portion of the hydrates in the flow stream are seen to have dissolved due to the methanol. The hydrate mass in the middle of the liquid flow stream is dissolving due to the methanol. Hydrates remain on the surface of the pipe walls.

Figure 77 and 78 shows that the methanol has cleared the hydrates in bottom portion of the flow stream. This is the dark patch in the lower center of the image. A significant quantity of hydrates still remain on the pipe wall and will rapidly create new constrictions. Figure 78 provides the effect of the methanol after some time elapsed.

Figure 87. Hydrate free stream in middle of flow line due to methanol.
Next a methanol slug was injected upstream of the condensed hydrate test section. A transient was introduced in order to distribute the methanol adequately to the walls to coat the hydrate surface with methanol.

Figure 88. Methanol slug injected upstream of hydrates on pipe wall.
Figure 80 is an axial view that shows the aftermath of injecting a methanol slug upstream after figure 79. A flow rate transient was created to put the liquid into the annular flow regime and distribute the methanol to the pipe walls. It should be noted that the method slug method has not been optimized to remove all of the hydrates. It does appear to hold substantial promise for routine maintenance practice.

The hydrates in figure 80 are seen to be disintegrating from the pipewalls and liquid is being transported to the view window surface. This suggests that using a transient procedure to inject methanol slugs is the method of choice for clearing the flow lines of hydrates.

Figure 89. Methanol transient slug removes pipe wall hydrates
Although the image in figure 80 shows hydrates remaining on the pipe wall, it can be concluded from this image that methanol slugs, injected in a manner that induces annular flow of the methanol, appears to be more effective that a hydrate drip as the means to clear hydrates created by condensation off of the pipe wall. Under normal low flow conditions in the storage field, annular flow conditions will need to be induced. This is accomplished by creating a differential pressure across a section of flow line. The pressure differential will create a gas velocity that distributes the methanol to the walls of the pipe.

Additional hydrate flow test data are being acquired to assess the effect methanol distributions other distributions of hydrates in the flow line.

5.5. Gas Storage Field Hydrate Monitoring and Control
The goal of flow monitoring for hydrate control is to identify the real-time condition of the flow lines and to manage and avoid fluid conditions that lead to hydrate constrictions and flow stoppages due to hydrate blockages in the lines.

Previous sections of this report provided visual data that helps to identify the prevalent conditions in storage field flow lines as a function of low velocity free liquids, condensing water, and water in a riser section. The data show that once operations are inside of the hydrate formation phase boundary, hydrates will be prevalent in the system. It is very difficult and costly to provide flow surveillance to identify, on a real-time basis, and monitor the physical condition of hydrates in every portion of surface and subsurface flow lines in the gas storage field.

The condition of the hydrates depends on the type of flow environment. In general, both free liquid hydrates and condensed hydrates are expected to simultaneously be present. The distribution of the hydrate masses is expected to be uneven throughout flow lines. Hydrate distribution is due to gas cycling and transient flow conditions at start-up.

Proactive hydrate control can be accomplished at locations in the storage field where hydrate constrictions and blockages are an identified problem. The control is achieved by linking pressure, temperature, and flow monitoring measurements. The instrumentation is used to automate hydrate control. The methods can also be used in other portions of the field where hydrate constrictions are present but have not been identified because full blockages have not developed.

Figure 81 provides data from an orifice plate during the development of a hydrate blockage in a downstream test section. The data is from the non-isothermal test section of the loop, figure 7. A series of start-up, steady state operations, shut-ins and re-starts were necessary to initiate the development of the hydrate blockage in the test section. This behavior is similar to the behavior of hydrates in gas storage fields as gas control changes gas requirements from the field.

Figure 81 provides differential pressure data across the orifice plate and pressure data across the hydrate blockage section of the test loop. The data shows the change in these readings as a function of time. It provides a measure of the development of the hydrate blockages. The first thing to note is that the flow rate is dropping. The second item to note is the change in the pressure across the test section and that the pressure fluctuations. The last item is the pressure drop across the section is increasing. Together, these are a clear indication of a hydrate constriction and a hydrate blockage developing.
Figure 90. Non-isothermal data showing the development of a hydrate blockage at the test facility.

Figure 82 provides a similar series of test measurements that were made from the isothermal test section of the test loop. In this section it was possible to observe the hydrate mass develop in the differential pressure measurements prior to the full development of a hydrate blockage. The plot shows differential pressure vs. time in the test section.

Figure 91. Isothermal data showing of the development of a hydrate blockage at the test facility.
The previous figures from the hydrate test facility show that practical hydrate monitoring can be accomplished in the storage field by monitoring the flow rate and the pressure. The data show that coupling two or more standard low cost measurements, within relatively close proximity of a blockage region in the storage field, permits sensing a developing flow constriction and blockage.

5.6. Practical Determination of System Susceptibility

5.6.1. Hydrate control flow diagram

This section of the report provides a hydrate control flow diagram and practical hydrate control issues. It is intended to facilitate field specific considerations required to manage flow line fluids, constrictions and blockage problems caused by gas hydrates. The diagram identifies specific points in the field for operators to consider as locations for hydrate control.

Natural gas fluid characteristics vary depending on the type of storage field, seasonal operating constraints, facility infrastructure, gas quality. Hydrates are difficult to manage because of the variability in storage field fluid behavior and the flow rate characteristics that drive liquid and hydrate transport and deposition as a function of operating conditions and field practices.

The flow diagram provided in this section identifies key variables that impact hydrate control at specific locations. The choice of monitoring method at a hydrate control point depends on the equipment and operation practice at field locations where hydrates are known to form or where water is present.

Multivariable and multipoint monitoring provides the most comprehensive means to deduce flow status and fluid condition in the flow lines. Different hydrate control points will experience different hydrate flow regimes. The hydrate flow regimes depend on the operating conditions, the amount of free liquid, maintenance practices, and the time a given fluid element is in the flow lines.

The field variables that can be selected for implementation depend upon the hydrate control technology that is used. Choices include water separation, flow control, temperature, pressure, chemical inhibition, heat addition, expansion control, and combinations of the above.

In general, it is important to know the gas flow rate, gas pressure, gas temperature, pipe wall temperature and water rates for the hydrate control points. These variables are used to monitor gas and liquid flow, pressure drops, operating zones, and hydrate inhibition requirements.
The flow diagram is a general diagram. It is not intended to be a solution for all storage fields, rather it is a guide. Each storage field, well and operating condition is physically different. Differences in the gathering system design, physical layout and operating practices drive the location of hydrate formation, transport, deposition, obstructions and blockages.
5.6.2. **Hydrate Control Flow Diagram**

Figure 92. Flow Diagram for Hydrate Control in Gas Storage Fields.

**Flow Diagram for Hydrate Control**
Figure 93. (continued) Flow Diagram for Hydrate Control in Gas Storage Fields

HYDRATE CONTROL FOR GAS STORAGE

FLOW DIAGRAM (CONTINUED)
The user of the flow diagram should not replace local hydrate experience with this diagram. Rather the diagrams should be used to supplement local field experience and help to support tailor insight on local hydrate control practices in the field.

The diagram should help isolate and identify causes and cures for hydrate flow constrictions and blockages at specific field locations. It can be used to trace any field hydrate problems back to the source of the problem in the field and then used to develop a strategy to help eliminate future hydrate problems.

The flow diagram is not intended to stand alone. It needs to be connected to the phase equilibrium diagrams, the chemical inhibition diagram, and the operating zone diagrams provided in this report. It should also be connected to the gas and liquid flow rates as a function of time at particular locations.

The diagram recognizes that much of this data may not be readily available at all locations in the storage field. Hopefully it can help provide the technical basis necessary to obtain the support required to improve field monitoring equipment and related operational practices.

In general, a procedure for using the flow diagram would be as follows:

- Examine the flow diagram and identify which pieces apply to the system that is being analyzed.
- Identify the range of operating conditions, i.e. temperatures, pressures, compositions, gas and liquid flow rates, methanol rates, etc. around that system. If the data are not available, estimate the ranges.
- Identify the types of flow conditions.
- Identify the variation times for those operating conditions based on time of year and gas control demands. If the data are not available, estimate the variation times (e.g. injection, withdrawal, cycling periods, drip cycles, shut-in periods).
- Construct a phase diagram (e.g. figure 29).
- Construct an operational risk diagram as a function of time based on the operating ranges from the above data by superimposing phase diagram over operating regions, e.g. figure 79.
- Identify where hydrates formation problems begin in the system.
- Prepare a water balance.
- Devise a monitoring strategy for the specific location, i.e. T, P, dp, Q.
- Prepare an inhibitor balance based on the specifics of the location.
- Prepare inhibitor P-T diagram.
- Prepare an inhibitor control strategy based on the location.
- Implement the hydrate control strategy in the field.
Figure 84. is an example of a hydrate control operational risk diagram. The phase boundary shifts according to the gas composition. Hydrate control includes the phase boundary shift due to the amount of methanol relative to the amount of water in the flow line at a particular location. The isothermal condition is the sub-surface ground temperature. The non-isothermal conditions include the gas temperature, process equipment temperatures, and ambient temperature conditions.

Figure 94. Example hydrate formation risk zone vs. operating regions for different gas types.
5.7. **Practical Inhibition/Control Issues**

5.7.1. **Methanol distribution in flow lines**

The effectiveness of methanol in the flow lines depends upon:

1) the amount of methanol relative to the total mass of water in the flow line at that location,

2) the distribution of methanol relative to the location of hydrates in the flow line,

3) the distribution of the methanol caused by the flow rate.

The amount of water that is in a flow line will vary depending on the layout of the system and the operating characteristics of the field. Methanol should be injected into the flow line in a manner that distributes it effectively into the water phase, onto any hydrates, and on the pipe walls.

The field engineer responsible for injecting methanol needs to know the amount of water in the flow lines, as well as the gas composition, temperature and pressure conditions. This data is typically not available at many locations.

If free water is expected, the amount of water in the flow lines should be established by flow measurement in the field. This is needed so the correct amount of methanol is injected in order for the hydrate control to be completely effective. It is better to measure the liquid water flow and inject the correct amount of methanol for the measured water flow. This will avoid under-inhibiting the water phase.

It should be noted that under inhibition with methanol may exacerbate hydrate problems. The methanol concentration prior to injection into the flow line needs to be checked to make certain that it is not diluted with water or other chemicals. It is important to verify via measurements the actual concentration of the methanol provided by the methanol supplier, methanol should not be blended with other chemicals compounds or water. This will help insure that the correct concentration of methanol will be injected into the flow lines to control hydrates.

It is also important to identify points in the flow systems where flow streams are combined and additional water may be present. These are locations where the water stream may be under-inhibited due to the excess water.
5.7.2. Shut-in: hydrate prevention methanol slug

Shut-in conditions create optimal conditions for hydrates to grow and to provide the precursors for hydrate blockages to develop. This is the period when hydrate masses are accumulating on any free water in the pipe and on the pipe walls. Start-up conditions disrupt the hydrates and cause them to agglomerate.

An effective means to hydrate control at critical locations is to inject a slug of methanol prior to shut-in the gas in. The slug of methanol should be distributed throughout the flow line by the gas velocity, i.e. annular flow conditions. This can be accomplished by achieving flow velocities of greater than 10-15 ft/sec.

5.7.3. Start-up: hydrate prevention methanol slug

During start-up pressure transient occur in the flow lines. Typically this pressure creates a high gas velocity that can strip loose hydrate material from the pipe walls and force hydrate masses downstream to create flow line constrictions. This will throw all of the material downstream to a point where the pressure has been close to being equalized and the velocity has been reduced to the production flow rate.

In a similar manner to shut-in treatment, a slug of methanol can be injected prior to start-up at critical locations. The slug of methanol should be distributed throughout the flow line by the gas velocity, i.e. annular flow conditions, see figure 77.

5.7.4. Gas Shut-in Conditions With and Without Methanol

It is suggested that a slug of methanol be injected prior to shut-in in areas where hydrates are known to develop and cause problems. This will eliminate or reduce the amount of hydrates present in the flow lines during shut-in. It is pre-emptive action and will facilitate start-up and reduce post shut-in blockage developments.

Gas Start-up Conditions With / Without Methanol

This is the typical effect that field personnel hear during start-up conditions, i.e. rocks bouncing down the pipe. The rocks will accumulate and produce a flow blockage. Start-up should be initiated slowly. It may be prudent to inject a slug of methanol at start-up to help wash and dissolve any hydrates that exist on the pipe walls. The pressure transient can be utilized to create a high velocity gas that will put a slug of methanol into the annular flow regime. In this regime methanol will wash all existing hydrates from the wall of the downstream flow lines.
5.8. **Practical Blockage Removal Issues**

5.8.1. **Hydrate Control**

The best suggested procedure for controlling and/or eliminating hydrate plugs is to continuously monitor and control the amount of water in the flow lines. This can be accomplished by improving water separation methods at the source, and/or by adding inhibitor in the right amount and manner upstream of locations that are prone to hydrate problems following the suggestions in the previous sections of this report.

5.8.2. **Hydrate Line Depressurization**

Line depressurization is typically the best means to decompose a hydrate blockage. It utilizes the fundamental behavior of hydrates as indicated by the phase diagram. Typically depressurization is a slow process that is restricted by mass transfer from the hydrate interface. Depressurization needs to be done properly, in a safe manner, from both sides of the hydrate plug maintaining a low differential pressure across the blockage.

5.8.3. **Line Heating to Remove Blockage**

This may create a safety concern. Company procedures, practices and safety personnel should be consulted. In general when a hydrate blockage forms it is prudent to assume that more than one blockage is present. Line heating in general is not recommended as the means to eliminate a hydrate blockage.

5.8.4. **Methanol Injection to Remove Blockage**

Although methanol is a good hydrate inhibitor, methanol can be a safety concern when used to remove a hydrate plug. Methanol injection can be used if some flow is still possible so the inhibitor can reach the hydrate. If flow is stopped then the methanol may not reach the plug. Methanol flow can be held-up by a substantial hydrate blockage which will slowly dissolve over time.

It is not recommended to use methanol if a hydrate blockage is fully developed and no significant flow is possible to deliver the inhibitor to the location of the blockage.
5.8.5. Use of Pressure Transients to Remove Blockages

Pressure transients may create safety concerns. The application of a large pressure transient to dislodge a hydrate blockage through a large differential driving force can induce a hydrate plug to loosen and achieve very high velocities in the flow lines, consequently the application of high pressure transients is not recommended.

Ideally the differential pressure across the plug needs to be controlled to prevent an unsafe condition from arising.

5.8.6. Pigging to Remove a Blockage

Pigging can be used to clean up hydrates from the pipe walls. It should not be used to dislodge a plug since this relies on a significant differential pressure. A slug of methanol typically would precede the pig.

5.9. Example Data - Latigo Storage Field

5.9.1. Operating Conditions/ Hydrate Occurrence

Flow constrictions and flow blockage development due to hydrates in the gas storage field is a dynamic process. Hydrate blockages depend on many variables including the type of water production (free or condensed), geological environment of the field, and the field operating flow conditions and characteristics including seasonal production requirements and gas control directives. It is possible to operate inside of the hydrate phase boundary and not develop a hydrate blockage. The phase diagrams make it clear that many storage field locations are operating with gas hydrates in their flow lines.

Initial withdrawal of gas from the production well provides a warm gas source. The warm gas is saturated with water. The conditions are far above the hydrate phase boundary. As gas moves towards the surface, it cools and water begins to condense. The condensed water is carried along by the gas velocity as long as it is above a critical velocity value. For a given gas composition once the temperature and pressure in the tubing or casing reaches the hydrate phase boundary, hydrate formation will begin.

At the surface the heat from the gas stream or separator is carried from non-isothermal regions in the well and surface equipment to a subsurface isothermal region. The equilibrium boundary fluctuates. The isothermal region includes subsurface gathering lines drips, and trunklines.

Compression and injection cycling moves gas and any free liquids in the flow lines towards the well. The reverse transport of liquid is dependent upon the gas velocity.
Relatively low gas velocities, i.e. approximately four ft./sec and less are sufficient to move free liquid over flow line terrain elements. This forces liquids back in the direction of the well.

Shut-in conditions cause the flowlines to equilibrate with the ambient temperature conditions. In each case the amount of water that is present in the flow lines varies depending on the location and operation specifics.

Figure 85 shows the Latigo field site. The site consists of the production tree, 6" flow lines, separator, methanol drips, orifice measurement, subsurface flow lines, elevation changes and a subsurface drip which is located approximately 200 yards from the well.

5.9.2. Facility Experiments and Instrumentation/Data Analysis

Figure 86 is an example of a daily data log of temperature and pressure at different locations along the flow line. Data is acquired at a rate of once a minute. It is an example of the variation in the operating conditions that fluids in the flow line encounter over a twenty-four hour period. The Latigo gas composition is provided in Table 2.

Superimposing the operating conditions over the hydrate phase diagram produces a hydrate risk diagram as shown in figure 84 for the Latigo gas mixture. Figure 86 shows
that the pressure at this site is in the range from approximately 800 psia to nearly 2000 psia, and temperatures range from about 85 °F to approximately 10 °F.

Figure 96. Latigo example pressure and temperature conditions vs. time.

Table 3. is the gas analysis from the Latigo field site. The gas analysis shows a number of heavy hydrocarbon constituents. These presence of the higher hydrocarbon components causes a significant shift the hydrocarbon phase boundary to temperatures that are above the hydrate formation phase boundary. This means that condensate is present in the flow lines. Figures 41 and 60 showed the effect of condensate on hydrate formation.

Table 3. Latigo storage gas phase sample composition analysis.

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Table 4 is a detailed analysis of the liquid condensate phase. Although small, the concentration of the light hydrocarbon in the liquid phase is significant. In addition to the generating hydrates at the gas and liquid water interface, the light hydrocarbon components promote hydrate formation at the liquid hydrocarbon and liquid water interface for condensates. Flow studies are in progress at the hydrate flow test facility to determine how the hydrated condensate phase is transported in low flow rate flow lines and to see the effect of methanol on this phase under flowing conditions.

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</tr>
<tr>
<td>4-METHYLINDANE</td>
<td>0.05</td>
<td>0.07</td>
<td>0.07</td>
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</tr>
</tbody>
</table>

The operating temperature, pressure, composition conditions determine the amount of water the gas phase can hold. It does not identify the free water that is delivered by the well by the gas flow to the surface flow lines. This needs to be determined at the well head.

Water exceeding the saturation concentration in the gas phase will condense on the flow lines and provide the basis for hydrate formation. The hydrate flow test facility data shows that the excess water is located on the walls of the pipe and in the bottom of the pipe.
Figure 87 and figure 88 provide a plots of the mass of water based on the gas temperature, wall temperatures, and skin temperature. The difference between the gas temperature and surface temperatures drives the condensation process from the gas phase.

**Figure 97. Estimated amount of water and temperature variation vs. time.**

![Graph showing estimated water and temperature variation vs. time.](image)

**Figure 98. Variation in estimated water output and temperature vs. time.**

![Graph showing variation in estimated water output and temperature vs. time.](image)

In addition to water from the gas phase, produced water may also be present. It is the free water in the flow lines. Produced water needs to be measured at the well-head. The total amount of water, i.e. condensing water and produced water and the expected.
operating conditions determines the required methanol injection rate at a particular field location.

Figure 89 provides data from the field test site that shows a normal orifice differential pressure reading over a twenty-four hour period of time. The data is recorded every minute. The data is well behaved as expected.

Figure 99. Orifice differential pressure and flow rate reading at field test location.

![Graph](image)

Figure 90 provides field data obtained at the same orifice meter location. The data begins at mid-night and appears well behaved although the flow can be seen to be dropping. About 2:30 am the differential pressure readings become very erratic with a clear decreasing trend in the readings, i.e. reduction in the output. The trend in the data indicates that the flow is rapidly decreasing. It is reduced to at times to nearly zero.

The trend in the differential pressures and flow rate is reversed around 5:30 am. The differential pressure across the orifice steadily increases after that point to its steady state flow rate. Flow increases until around 8:00 am when it returns to normal as observed by the differential pressure data.
Figure 100. Differential pressure data showing erratic flow behavior consistent with hydrate blockage development.

Real-time monitoring of the differential pressure provides a means to observe the dynamic behavior of the flow in the flow line. Coupling this to type of monitoring to operational risk diagrams and effective hydrate control with methanol should reduce hydrate constrictions and flow blockages.

An important and difficult component in the field tests was data acquisition. It is important to provide a simple system that is not tied into all of the other data acquisition systems that proliferate in various field locations.
5.9.3. Application to Field Operations

All of the data provided in this report is directly applicable to field operations. Nothing provided here is difficult or costly to implement. The most difficult part will be identifying a field based strategic plan for upgrading instrumentation and methanol injection for flow blockage control in the gas storage field. A list of site priority locations needs to be developed at each storage field that is prone to hydrate constrictions and hydrate blockages. This document provides the strategic technical basis that should facilitate that effort for gas storage field operators.

Certain types of data are currently difficult to acquire in the field, i.e. wet gas measurements at the well-head. These data would provide the basis for optimizing hydrate control with methanol. Field implementations should be designed to accommodate future advances in flow measurement that will address small quantities of produced liquids.
5.10. Example Data – Greenlick Storage Field

A substantial set of standard operating data has been acquired from the Greenlick storage field site (400 worksheets were acquired with over 700000 data conditions). Equipment limitations were necessary due to the high operating pressures at the site and the associated problems which protruding equipment causes in flow lines. All of the Greenlick data has been collected and exists in Excel spreadsheets and charts. Additional work remains to clean up the tables and Excel charts. The tests that were conducted at the hydrate flow lab and the associated findings are consistent with the empirical data and conditions identified at this field site. A comprehensive set of Greenlick hydrate diagrams is provided in the appendix of this report.

Figure 102. Example of hydrate mass produced from the Greenlick storage field flow lines.
5.11. Greenlick Storage Field Data

Figure 103. Greenlick flowline orientations.
6. Review of In-line Rotary Compact Separators For Liquid and Hydrate Control

6.1. Overview

An overview on gas storage field separation and separator issues is provided along with a discussion of sources of water in gas storage fields. This is followed by a review of traditional gravity based separators in order to provide a reference point for the subsequent section on in-line compact rotary separators. The compact separator section reviews the benefits of compact separator technology relative to conventional separator technology. It discusses the basic operating principles that underlie in-line compact rotary separator technology. Examples of separator performance are provided from CEESI's flow laboratory and field measured data. Lastly, equipment specification requirements, operating issues, and maintenance considerations are listed. The report concludes with its recommendations on how to advance the evaluation, development and implementation of the technology for gas storage field operations.

Water and liquid production from gas storage fields is common. The problems caused by water effect flow control, deliverability, maintenance, operating efficiencies, safety and operating costs. Ultimately the presence of water in the flow substantially increases business risks due to an increase in operating uncertainty. Efficient control and removal of water at the well head and flow lines is a priority for operators. Water in the flow lines leads to a number of challenges including: well-bore and flow line degradation, scale deposition, scale induced blockages, hydrate flow constrictions, hydrate blockages, gas flow monitoring and measurement errors caused by wet gas and hydrates, flow line corrosion sensor failures, transmitter failures, flow line equipment failures, high chemical treatment expenses for corrosion, bacteria and hydrate control, and environmental disposal issues.

Water management and removal needs to progress beyond basic liquid knock-out designs and related equipment. This is needed in order to provide a more efficient and comprehensive solution to water management and control. Traditional gas storage field water management encourages the approach of treating water related problems as distinct issues. This is driven more by technological necessity than design. The work reported here initiates an approach that tries to offer a cohesive engineering strategy that will improve water control and reduce the problems it produces in storage field flow lines and facilities. It recognizes that this is a long term issue and challenge for the industry.

Advancing water control in the field requires: (1) a systematic technical approach that provides practical value in terms of water control for storage field operators,
(2) equipment options that are consistent with those strategies, (3) a utilitarian
definition of “separator efficiency” and (4) laboratory and operating data that
demonstrates and validates improved water control methods. This is necessary in
order to justify augmenting or altering current engineering practices for water
separation and control.

This report provides an initial study to support the analysis and inevitable use of
small, in-line rotary compact separator technology in gas storage applications.
The overall goal is to help minimize problems in storage fields caused by water.
It is a starting point that reviews the technology in order to help advance water
management and hydrate control options for gas storage operators. It
complements previous GRI and CEESI hydrate control laboratory and field data
work. In-line, compact, rotary separator technology is an emerging separation
technology. It advances the separation approaches and options that are available
to control and remove produced hydrocarbon, free and briny water, particulates,
and foams from gas production facilities. At its core, this “new” technology relies
on the same underlying principles that are applied in conventional separator
technology. In-line compact rotary separators accomplish the task through a
relatively novel design and significantly more efficient package.

6.1.1. **Sources and Types of Water In Flow Lines**

The gas that is injected into a storage facility is usually pipeline quality gas which
has been dehydrated to meet pipeline specifications. The reservoir where the gas
is to be stored prior to extraction has water that is present in the pore space of the
rock. When pipeline quality gas contacts the water at the significantly higher
subsurface temperature conditions in the well, the water in the reservoir will
vaporize and saturate the previously dried gas phase. The water that vaporizes
may be come from an active water drive or from connate water. If the water is
from an aquifer, water will eventually reach the wellbore as the well is produced
over a season. During withdrawal of the injected gas from the storage reservoir,
the temperature changes dramatically from the bottom hole temperature of the
well to the surface conditions. As gas is produced and flows to the surface its
temperature is reduced. The lower temperature drives condensation of the water
from the gas phase and causes it to condense in the flow lines. The gas flow rate
drags the condensed liquid water up the casing or tubing to the surface where it is
co-produced with the gas phase. This assumes the gas flow rate exceeds the
critical particle velocity. In principle free water should be removed by the knock­
out separator. If the gas flow rate is high enough it will entrain any free water and
by-pass the separator regardless of any internal baffles or demisters in the
separator.

Water is produced from the storage field reservoir as free liquid water, entrained
liquid in the gas flow, and as water saturated gas. Each source of water has its
own chemical character, fluid transport characteristics, and engineering control
options. Each source of water has its own characteristic set of problems caused by the underlying water chemistry.

Free water is considered here as produced liquid water (connate or interstitial water) from the reservoir that has been carried to the surface in the liquid phase by the gas production flow rate from the well. Saturated water is water from the reservoir that has evaporated and saturated the gas phase. It is carried by the gas phase flow as water in the vapor state. It saturates the gas phase in the well-bore at the well-bore operating temperature and pressure conditions. Free water and saturated water are mixed in the flow stream as the gas is transported in the well-bore to the surface. This mixing process drives the chemical dynamics associated with mineral dissolution and deposition in the well-bore and downstream flow lines. As production flow rates and flow conditions in the well bore vary, the relative proportions of each type of water changes accordingly. This is a dynamic process.

Water is also present as residual hold-up water in storage flow lines. The hold-up water occurs due to low gas flow rates and during shut-in and withdrawal periods due to condensation and separator upsets. Oversized flow lines are often the cause of water hold-up. The movement of the liquids in the flow lines depends on the location of the line, transients, and the type of operation, i.e. injection or withdrawal.

Once in the flow lines, water may exist in any number of states: (1) as liquid with or without minerals, with chemical and biological inhibitors and hydrocarbons, (2) as solid in hydrate, (3) as solid in ice form, and (4) as a vapor in the gas phase, and (5) as an emulsion when condensate is present. Each state has its own physical property characteristics. For example, the components in the liquid state affect the operating conditions at which hydrates form. Scale deposition in the flow line can produce constrictions which create an internal nozzle shape configuration in the flow line. This constricts the flow and encourages blockage development. If the fluid is briny, then hydrates will form at lower operating temperatures and higher pressures. If the brine has been knocked-out in a separator, then hydrates will form at higher temperature conditions.

Fluid movement in the flow lines depends on the specifics of the flow lines and field operations. Water movement in the flow lines is often bi-directional. The liquid flow rate and flow velocity pattern at a particular location in the flow line will determine how the fluid moves in the flow lines, i.e. entrained, annular, stratified, or as a slug, in addition to the route it will take. The local flow regime depends on the quantity of fluid, any constrictions in the flow line and orientation of the flow line. Two phase flow patterns in storage field lines range from: (1) bubble flow (where a portion of the flow line is dominated by liquid and gas bubbles rising through the liquid due to a pressure differential), (2) slug (large bubbles of gas aggregate in the flow through the liquid phase), (3) semi-annular (combination of liquid and gas dominated flow), (4) annular flow (where the large
amount of liquid is forced to the wall of the flow line (high center velocity of gas flow), and (5) mist flow (where the high velocity gas shears a small quantity of liquid into minute droplets that are carried in the flow stream). Flow may be both co-current and counter-current to the gas flow. It depends on the quantity of liquid, location and orientation of the flow line.

The operating choice and operating convenience of water removal technology depends on the state condition and location of the water, (solid, liquid, gas and or combinations of them). It further depends on a number of key operating variables. The variables include the temperature, pressure, gas flow velocity, flow line configurations and operating dynamics. The type and quantity of water produced influences the separation method that is used to remove and/or manage it.

Determining the quantity (rate) and quality of fluid is critically important in order to accurately assess, control and treat water in a manner that mitigates water related problems in gas storage field flow lines. This can be accomplished through the development, testing, validation and implementation in the field of reliable separation and flow related measurement devices.

6.2. Gas Storage Field Separators

An overview of conventional storage field separation devices is provided as a reference point for evaluating the design, performance and benefit characteristics of inline compact rotary separators. The discussion focuses on two phase knock-out separators which are the most common ones found in gas storage field facilities.

Gas storage field separators are pressure vessels that are generally designed to handle high gas to liquid ratios. The liquid phase is typically water, although small amounts of condensed hydrocarbons may be present in the flow stream. The quantity of liquid hydrocarbons depends on the storage field reservoir characteristics. The water typically contains varying amounts of dissolved minerals. The quantity of dissolved minerals depends on the field. Separating liquids from the gas stream is accomplished by using any of three general types of separator designs: (1) horizontal separator, (2) vertical separator, or (3) spherical separator. The choice of separator depends on its function, company specific practices and the history of the facility. Beyond the functional needs of the separator, separator designs are distinguished by the internal components and their configuration within the separator.

6.3. Conventional Separator Technology

The primary function of any field separation unit is to: (1) remove the liquid stream from the gas stream, (2) minimize the carry over of any entrained liquids
in the gas stream into the downstream flow lines and (3) provide separate flow paths for the liquid stream and gas streams.

In general, the performance of static, gravity based separators relies, to a large extent, on the assumption of steady-state operations. They require the following features of the separator in order to achieve adequate separator performance, control and safety: (1) the velocity of the gas must be lowered from the well-head gas velocity so gravity is the dominate force acting on the liquid and particulate streams, (2) turbulence is minimized to reduce entrain droplet and particulate carry-over, (3) an equilibrium condition is approached in the separator vessel, (4) fluid foaming characteristics are minimized or eliminated, (5) re-entrainment of the separated gas and liquid streams is controlled, (6) outlet pressures are regulated, (7) temperatures regulated, (8) liquid levels are controlled, (9) routine maintenance options are available, (10) safety controls are provided should a blockage of a gas or liquid line occur, (11) sensors are utilized to monitor pressure, temperatures, liquid - levels, and in some cases, (12) fluid flow rates for monitoring and audit purposes.

Principal considerations in the separator unit are: (1) the amount of liquid that is to separated during operating periods (e.g. gallons or barrels of liquid per day under operating flow conditions), (2) gas flow rates, (3) fluid densities, (4) temperature and pressure range, (4) presence of solids, (5) foaming considerations.

Common components that are found in the different geometrical configurations of horizontal, vertical and spherical separators include 1) a diverter that is used in the bulk fluid separation section of the separator to redirect the gas and liquid phase flow, 2) vanes that are used to provide a contact surface and facilitate liquid droplet aggregation, 3) wire mesh at the gas outlet to reduce entrainment and facilitate coalescing of small liquid droplets, 4) downcomers to direct aggregated liquid to the liquid outlet region, 5) liquid outlet and gas outlets, 6) level controls and monitors.

In general traditional separators contain four basic sections. The sections are: (1) primary separation section, (2) the gravity section, (3) coalescing, and liquid collection section and (4) fluid removal sections.

The primary separator section may consist of an oriented inlet nozzle and diverter. The orientation of the inlet and diverter determines the initial fluid flow direction of the phases. The diverter baffle forces a change in the momentum of the fluid. It causes a change in the direction of a major portion of the liquid and or solids from the gas stream. The gravity section reduces the velocity of the gas and turbulence to facilitate the dominance of gravity forces over the gas flow forces. This is utilized to control the dropout of entrained liquid particles from the gas stream in the separator. It also provides a large contact surface area for entrained gas to degas from the liquid phase. The coalescing section of the separator captures
small liquid droplets by providing a tortuous contact surface where the liquid particles can aggregate and be removed from the gas stream. It may also include a downcomer to direct the liquid to the outlet. Lastly, the liquid collection section receives all dense fluids and solid particles from the inlet, gravity and coalescing sections and removes them to a separate liquid flow line. Traditional gravity based separators are designed for steady state flow conditions with a sizing margin of safety for controlling liquid surges. High flow velocities or transient induced flow may produce an unanticipated change in separator performance. This will result in poor separator efficiencies and downstream problems caused by liquid carry over from the separator.

In gravity based separator designs, the separator vessel acts as an oversized section of piping. The separator retards the gas velocity. This permits gravity to dominate the forces acting on the liquid that is dragged and/or entrained by the flowing gas phase. They may or may not have a mist extractor. The efficiency of the separation is determined by the gas to liquid ratio, gas flow rate, and entrained liquid particle size distributions.

### 6.3.1. Horizontal Separators

Horizontal separators are the workhorse of gas field fluid separators and offer the most separation capability for their capacity. They are typically used on high gas to liquid ratio flow streams. They provide a large volume and surface area for the gas and liquid separation to occur. This gives a high residence time for gas entrained in the liquid phase to disengage from the liquid. Horizontal separators provide greater gas-liquid contact area through the use of internal baffles. Gas and condensed liquids flow on the baffles creating a liquid film that drains to the liquid outlet. The length of the baffles depends on the expected liquid particulate size and gas velocity. A wire mesh is sometimes included at the gas outlet. The mesh acts as a coalescing section at the gas outlet to further facilitate liquid dropout from the gas phase. The wire mesh can get plugged by solids and hydrates. Figure 1 provides a simplified illustration of a horizontal separator with the essential features. The use of 2/3 in the following figures means two or three fluid phases, i.e. gas, water, condensate.

![Figure 104: Schematic of two-phase horizontal separator](image)
Two phase horizontal separators can be configured with either a single separator chamber or in a double barrel configuration. A schematic of the double barrel configuration is not provided here. Horizontal separators can be easily skid-mounted, serviced and stacked into multi-stage units if required. Horizontal three phase separators have an additional section that separates the water compartment from the liquid hydrocarbon compartment with additional level and dump valves.

### 6.3.2. Vertical Separators

Vertical separators are often used when intermediate amounts of liquids are present in the flow stream. Vertical separators have a smaller installed foot print and offer better slug handling capabilities than horizontal separators. The orientation of the inlet nozzle in a vertical separator is used to impart a centrifugal two-phase fluid flow. The centrifugal motion causes the liquids to form a thin liquid film on the wall of the separator which facilitates gas and liquid separation. The fluid motion increases the residence time and contact area for the separation. The gas rises to the top of the separator and the liquid falls to the bottom. Small liquid particles can be swept along with the gas phase so a baffle or coalescing mesh may be used to aggregate liquid droplets at the top of the separator. Vertical separators have similar internal components to horizontal separators. Figure 2 provides a simplified schematic of a vertical two-phase separator.
Vertical separators can include down-comers (not drawn). The down-comers collect the condensed liquid droplets from the coalescing section. The down-comers reduce the condensed liquid exposure to the flowing gas stream, minimize the re-entrainment of liquids, and direct the condensed liquid flow from the coalescing filter to the liquid outlet in the bottom of the separator.

### 6.3.3. Spherical Separators

Spherical separators are used when high pressure, compact size and limited liquid handling is required. They have similar performance characteristics to horizontal separators and have a slight cost advantage due to their reduced size. Figure 3 provides a simplified schematic of a spherical two-phase separator.
As outlined, each separator has a specific advantage that depends on the specifics of the application. Changes in the flow characteristics will change the separator requirements. The performance depends on flow rates, fluid quantities, and fluid characteristics, e.g. emulsion handling capabilities. In general, the above separation technologies are established and well-known.

In addition to large vessel separators, flow line drips are widely utilized to accumulate free water from the gathering system flow lines. The drips are necessary because of inadequate performance of upstream separation facilities and liquids carried downstream by the flowing gas phase. In addition, drips may accumulate liquids from downstream operations that push gas and liquid towards the well-head. The drips are generally located at low points in the flow line. Drips are manually blown down by field maintenance personnel by utilizing the pressure in the flow line. Scheduled drip-line maintenance is required in order to prevent flow blockages and other problems from occurring with the drips. Schedules are developed from field technician experience with the particular location. Drips are physically inaccessible and not monitored. The required
6.4. **In-line Compact Rotary Drum Separators**

Conventional, gravity based separation is a mature technology. Relatively reliable devices have been available for many years to the gas industry. In general, conventional separation equipment has a large footprint and can be time consuming to install, operate and maintain. It often necessitates construction of permanent pads. Traditional separators may require supplemental energy to heat the unit to prevent freeze offs due to hydrates and ice during cold periods. Real-time liquid separator monitoring equipment, e.g. turbine flow meters are inaccurate and often impractical due to damaged caused by particulates and hydrates in the liquid stream. In general field communication and monitoring on the condition of the separator is not utilized.

Compact in-line rotary drum separators are an emerging field fluid separation and control technology that provides an alternative to conventional storage field separators. It can replace or augment existing gas storage field separator facilities. Compact separator technology has a number of advantageous features including: compact size, light weight, ability to scrub liquids from the gas stream, high throughput to size ratio, in-line installation, ease of retrofitting, relatively high efficiency, reduced liquid hold-up, foaming control characteristics, minimal instrumentation requirements, relatively low maintenance, ease in manufacturing, and power generation option capabilities. The separator can be installed to operate at the wellhead, as a pre-or post scrubber for a conventional separator and in the flow line at liquid gathering points. In addition they offer the potential for monitoring wet gas measurement. Wet gas measurement offers improved well, flow line, field and facility management.

CEESI has investigated the performance of in-line compact separators for steady flow operating conditions under different liquid loadings. The liquid phase in these studies consisted of liquid hydrocarbon. Little is known about their performance and operating characteristics in a more dynamic operating environment such as the conditions prevalent in a gas storage field. Gas storage field conditions include water as the dominant liquid phase. In addition the operating conditions often fall near or inside the hydrate phase boundary for extended time periods.

Figure 4 shows an installation of a 3" compact separator at the CEESI Flow Test Facility. The flow direction is from left to right. Liquid is withdrawn through the line located on the bottom of the device. Gas is re-circulated from the liquid removal side through a valve to the top of the device.
6.4.1. Benefits

The principal benefit of compact rotary drum separator technology is that it provides a compact, efficient separation alternative to conventional horizontal, vertical and spherical separators. In-line compact rotary separators can accomplish fluid separation in a significantly smaller package and footprint without sacrificing performance. This makes the technology a useful alternative that can extend, replace or complement existing separation packages. Another added benefit is that the unit can be used to generate power.

The unique design of compact in-line separator devices permits it provide the ability to scrub liquids from the gas stream while handling high gas throughput. In-line installation facilitates low cost and rapid retrofits to existing facilities. Its high separation efficiency under steady state operating conditions reduces entrained liquids in the gas phase. Foaming and particulates are less of a problem due to the way liquid is removed from the device. There are minimal instrumentation requirements. Maintenance requirements are considered low by the manufacturer. This needs to be verified through gas storage field testing. It is the only separator that has power generation capabilities, independent of using natural gas, in the gas storage field. The compact separator can be installed to
operate at the wellhead, as a pre- or post scrubber for a conventional separator and at any appropriate point in the flow line. It can be packaged in a skid-mount configuration for well testing. Lastly, it provides the opportunity for wet gas measurement at the well head. All of these features provide useful attributes for storage field operators. The only perceived downside to in-line compact rotary separators is the anticipation of higher maintenance requirements due to its moving parts.

6.4.2. Operating Principles

The concept behind the in-line compact rotary separator is that it uses inlet gas pressure across static nozzle vanes to generate high rotational flow forces. The rotation forces on the fluid particles replace static gravitation forces used in conventional separators. The rotating fluid drives an internal barrel. The centrifugal forces generate a high-g field that permits achieving high separation performance combined with the potential for energy recovery. Liquid is accumulated on the rotating surface and flow over the lip of the drum and collected into a chamber. Energy can be recovered as high liquid pressure, shaft power or as a combination of both. A pressure differential of 0.5 to 5% of inlet pressure across the device is used. The design for the compact separator takes advantage of the difference in the momentum and induced centrifugal forces on the gas and liquid phases, as well as any particulates and foams, as they rotate in the device.

Rotary separators utilize the line pressure to achieve a bulk two phase separation. A portion of the pressure energy in the two phase flow is converted to kinetic energy by the accelerating the fluid mixture through inlet nozzles or diverter blades. Shear forces cause liquid particles to break into smaller droplets. The droplets. This is the primary separation point. The nozzles or blades induce the flow into a vortex flow pattern. The flow increases the effective path length, size and surface area for liquid contact with a liquid film dropout from the gas phase.

The density difference between the phases causes the gas phase to accelerate more rapidly than the liquid phase particles. The two-phase, gas and liquid droplets impinge at a near tangential angle onto the inner surface of the rotating cylindrical rotor. Viscous coupling between the liquid and liquid on the rotor surface facilitates the liquid disengaging from the gas onto the rotor surface.

Energy is transferred by drag forces when the liquid from the inlet is slowed down to the rotor speed. The liquids angular momentum is reduced to facilitate removal from the device and nominally increases the recoverable energy.

In one rotary separator design a diffuser scoop was utilized for removal of the liquid from the rotor rim. The design of the diffuser scoop seeks to maintain a constant liquid layer through changes in liquid flow rate, minimizes gas
entrainment in the discharged liquid, and results the re-entrainment of liquid into the gas discharge from the turbine.

Kinetic energy from the gas drives the rotor to a speed that provides a high-g field. The energy can be recovered as shaft power. The amount of recoverable energy depends on the speed and diameter of the turbine.

The general layout of the device consists of a swirl generating section, fluid separation zone, diffuser section and collection belt. The inlet contains the swirl generating section, pipe flange, liquid collection belt, and bearing housing. The exit portion contains the diffuser/flow straightening section, exit bearing housing and exhaust pipe flange. The rotor section contains a rotor drum pressed onto the shaft that provides the energy for rotation. The inlet and exhaust housings form the pressure containment vessel.

Figure 5 is a cross-section view of an in-line compact rotary drum separator. Two or three phase (2/3φ) fluids enter the device from the left. Liquids exit from the bottom and gas from the right.

Figure 108: Cross-sectional schematic of in-line compact rotary drum separator

An inlet nozzle section accelerates the inlet two phase fluid. The phases impinge nearly tangentially on a rotary drum which provides centrifugal forces and a contact surface to facilitate the separation in a low volume unit. The rotational velocity of the drum is determined by the momentum transfer from the two phase fluid. The centrifugal forces drive the high density particles to the separator rim. Liquid is captured by bringing high density rotating fluid particles in contact
with a rotating surface. The liquid is forced, by means of directional nozzles, to tangentially contact the rotating surface. This creates a liquid film which attaches to the surface. The efficiency of the separation is dependent on the operating parameters. The efficiency determines how much fluid will pass the separation point into downstream flow lines. Dump valves control the removed liquid level and escape valves return gas to the process line. Bearings are well-protected from sand and grit.

6.4.3. Compact Separator Performance Testing

A number of laboratory and field test trials have been performed on different configurations of rotary drum compact separators. The testing has been used to validate the general concept and performance of the technology.

Flow laboratory tests were conducted at CEESI to establish performance benchmarks in a controlled operating environment. Field trials were carried out to identify the degree to which the field performance could be expected to deviate from the laboratory benchmarks. An overview of the results of the laboratory and field testing of compact separator technology is summarized below.

6.4.4. Flow Lab Compact Separator Performance Data

A series of performance tests have been conducted on compact rotary separators at the CEESI flow test facility. The testing targeted defining the flow and separation characteristics of the compact rotary separator device under steady flow operating conditions. CEESI's test program investigated the separation characteristics using a dry processed gas stream provided to the facility from the El Paso/CIG system with a simulated condensate fluid, i.e. liquid Stoddard solvent. Stoddard is comprised mostly of decane. The testing did not use water as part of the test.

Figure 6 summarizes the trends that were observed in the CEESI flow laboratory data. The data were obtained at different gas velocities and liquid loadings. The chart presents the separation efficiency vs. the superficial gas velocity under different liquid loadings. The separation efficiency is defined as the percent of liquid removed from the inlet stream. The separation efficiency range is from around 98% to above 99%. It should be noted that the superficial gas velocities (gas velocity that would exist in the pipe without liquids present, i.e. gas throughput) are high compared to gas storage fields.

In general, high efficiency is achieved at relatively low loadings and high gas velocities. As liquid loadings increase and gas velocities decrease, a reduction in performance is observed. In the field this would result in liquids accumulating in low piping sections and in flow constriction points (e.g. orifice plates). The gas
Flow test data from CEESI versus separation efficiency followed the general trend shown in figure 6.

The testing at CEESI did not include many of the fluid and operational features that occur in gas storage fields. These conditions will affect the performance of the separator. Data should be obtained that demonstrates to field operators how the device should be installed and operated for storage applications. The above results represent ideal performance under steady-flow controlled laboratory conditions with well-conditioned fluids. No tests were performed with water, particulates or at hydrating operating conditions.

6.4.5. **Production Field Separator Test Data**

In addition to the laboratory testing at CEESI, field tests of the compact rotary separator were performed. The field tests were conducted by Chevron. The purpose of the field testing was to investigate the performance, operation and maintenance characteristics of the compact rotary separator under wet gas production conditions. The total field test time exceeded 4500 hours of operation.
The installation site consisted of production wells, gathering manifolds, scrubber separator, liquid storage tanks, and a gas custody transfer metering station. The produced gas consisted of natural gas, condensate and water from various wells. It flowed through a high pressure (ANSI Class 600) and low pressure (ANSI Class 150) manifolds. Dedicated horizontal separators (24'' x 10'') were used to remove liquids. The location of the field compact separator was upstream of the high pressure scrubber on the outlet of the 600 class manifold.

A test skid was designed to prevent interference with production at the site. The inlet, outlet and bypass piping matched the production header. The skid was designed to 600# ANSI operation and had a capacity of 12MMSCFD and 200 BPD of liquids.

Figure 7 shows performance characteristics under field operating conditions. The figure shows variations in the rotational speeds, pressure drop, gas flow rates, and liquid flow rates over several months of continual performance.

**Figure 110: Example field data from compact separator**

Example Data Trends of Compact Separator
With Variations in Gas and Liquid Flow Rates

In this example the rotational speed of the drum ranges from 2000 to 7000 RPM. The majority of the time is the drum is operating in a 4000 to 5000 RPM range.
Pressure drop ranges from 5 to 20 psig. Gas Flow is relatively constant at about 6 MMSCFD with liquid flow rates up to approximately 4 GPM.

Figure 8 provides an example of field performance from an in-line compact rotary separator. The data shows that separator efficiency ranges from 90 to 99 percent over the performance test period. The chart is an approximation to illustrate performance trends.

**Figure 111: Example field performance data of compact separator**

![Example Data Trends: Compact Separator Field Performance](image)

Figure 7 and 8 indicate the in-line rotary compact rotary separator is optimized for an optimal separation RPM relative to the fluid flow rate. Efficiency declines when the rotational speed of the drum is reduced below an optimal flow velocity.

The field test flow streams included foaming slugs and solids. The foam slugs appeared to clear themselves after a short time period. Visual inspections revealed that solid particulates were found in the field test unit. Samples of the solids were removed for identification. The solids included rust, silica quartz and clay. The liquid discharges holes of the separator were not plugged with solids. The upstream strainer (1/8") was inspected and did not show any solids. Visual inspection of the unit suggested that the unit can handle normal produced solids from a gas well and is self cleaning. No field tests have been performed with
water near or inside hydrate operating conditions. Testing was not carried out to identify scale deposition in the unit.

6.5. Recommendations

In-line compact separator technology is promising. Laboratory and limited field test data suggests that it can offer significant advantages over conventional separators without experiencing significant problems. However, before it can be expected to be used in gas storage field applications, it must overcome the expectation of increased maintenance/problems caused by the use of moving parts that are exposed to a harsh operating environment. Current data is encouraging. Ultimately only rigorous laboratory and field testing can provide unequivocal data that challenges high maintenance expectations.

A staged evaluation of in-line compact rotary separators is recommended prior to field testing and implementing compact separator technology in gas storage fields. The results of a staged evaluation would identify potential field issues and provide operators and field technicians with direct knowledge of the performance they can expect under realistic field operating conditions.

Stage 1 testing addresses the need to obtain data over a range of operating conditions (flow rates) with water, hydrates, and particulate loadings in the flow line. This can only be accomplished in a practical and comprehensive manner in a realistic water and hydrate flow test facility laboratory where all the variables can be controlled, monitored and evaluated. This stage would also identify improvements that should be made to prepare the technology for robust field applications. Stage 2 testing selects appropriate field locations so the technology can be tested at field operating conditions. This can be accomplished through a skid mounting of the units. Assuming that stage 1 and stage 2 are successful a third stage would advance the results to the commercial implementation stage for gas storage fields. It would include a detail economic analysis based on the actual performance numbers obtained for the technology during stage 1 and stage 2.

Stage 1:

1) Identify different storage field fluid types and operating characteristics that will impact in-line compact rotary separator performance.
2) Define specific test conditions with the gas storage operating committee.
3) Obtain simulated operating data that cover a range of liquid velocities, liquid loadings, operating conditions, and pressure drops.
4) Obtain performance at low temperature shut-in conditions.
5) Obtain performance data on inclined flow line regions.
6) Obtain data on reverse flow characteristics.
7) Provide summary data findings and use results to define Stage 2 locations for storage field testing.
Stage 2:
1) Based on results from stage 1, identify different storage field locations where the technology can be implemented under a variety of operating conditions, e.g. different water loadings, different gas velocities, different operating characteristics.
2) Map the data from the field to the flow laboratory results to validate data consistency.
3) Target implementation of in-line compact rotary separators at those sites where the performance can be accurately assessed.

Stage 3:
1) Commercial implementation based on an economic analysis (ROI).
2) Implement the in-line compact rotary separator in gas storage field locations based on promising results from obtained from stage 1, stage 2 and ROI analysis.

In addition to the items listed above the testing will need to consider: (1) controlling salt precipitation control through inlet nozzles, (2) static vs. dynamic separation design options and performance (dynamic vs. static rotation), (3) steady/unsteady state vs. transient performance behavior. It is expected that data on these items will obtained as the research progresses.

6.6. Compact separator recommendations

A review of in-line compact rotary separators for gas storage field applications indicates that the technology offers the opportunity for substantial benefits for water/liquid, hydrate, particulate and downstream scale control in gas storage field applications. The benefits are due to the unique compact design, portability, light weight, flexibility for in-line or skid mounted units, and technology integration opportunities.

A general discussion of traditional gravity based knock-out separators was provided that identified the performance metrics that must be achieved for competing technologies to be successful in the field. In-line compact rotary separators provide capabilities that far exceed typical field separator performance on a size basis. A discussion on the underlying principals of the in-line compact rotary separator highlighted the design and operating differences with traditional gravity based separators. Performance test data from the CEESI flow laboratory and the field demonstrates the level of separation performance. In general, the compact separator unit provided separation efficiencies of 95% or better for the test conditions. Low gas flow rates and operation transients may result in liquid carry-over to downstream flow lines. In addition, particulates may cause issues
with the technology. A number of data gaps were identified that are important to fill before the technology is used for gas storage field applications. A systematic staged testing approach was recommended in order to prepare the technology for applications in gas storage fields.

In conclusion, in-line compact separator technology offers significant and measurable benefits to gas storage field operators. A key benefit of the technology is that it reduces separator implementation barriers in gas storage fields. It can be easily used to reduce liquids that are held-up in flow lines in critical locations. In-line compact separators can be installed to operate at the wellhead, as a pre- or post scrubber for a conventional separator, and in the flow line. Lastly, the technology opens the opportunity for integrating a number of processes that will reduce downstream fluid control problems.

6.7. In-line Rotary Drum Compact Separator Considerations

6.7.1. Specifications Considerations

6.7.2. Operating Parameters

1. Temperature operating range
   i. Low temperature - 40°F
   ii. High temperature - 200°F
2. Pressure ratings
   i. Up to 2500# ANSI flanges (~6000psia)
3. Inlet Pressure operating range (typical)
   i. Low pressure ~ 5 psig
   ii. High pressure ~ 1400 psig
4. Pressure drop
   i. Low side - 0.5 % of inlet pressure
   ii. High side - 5% of inlet pressure
5. Liquid Capacity
   i. 4% by volume
6. Flow velocity
   i. Low end
   ii. High end
7. Operating efficiency
   i. Determined by carrying out a liquid mass balance between the inlet conditions and outlet (gas and liquid).
8. Scale and solids
   i. Upstream screening should be installed and maintained
9. RPM Range (depends on sizing)
   i. Minimum RPM ~ 1500
   ii. Maximum RPM ~ 10,000
10. Weight (size dependent) - 3" ~ 850 lbs.
11. Piping requirements (by-pass stream recommended)
12. Instrumentation needs (speed sensor provided)
13. Communication (extra)
14. Optimal operating point calculation depends on process conditions
   Material options – low vs. high pressure
   i. NACE compliance, 316 SS
   ii. Customized skids
   iii. Speed, pressure and vibration sensors
   iv. ANSI/Grayloc/compact flanges
15. Bearing considerations – replacement cycle
   i. Depends significantly on the operational characteristics, i.e.
      start-ups and shut-ins, cycling, pressure variations

6.7.3. Application Considerations

1. Liquid Phase: Specific gravity, water cut, viscosity
2. Gas: compressibility factor, molecular weight, viscosity
3. Flow line diameter
4. Flange rating and type
5. Solids present (quantity and size)
6. Pressure – design, normal, maximum, minimum
7. Available ΔP
8. Liquid flow rates
9. Gas flow rates
10. Operating temperature
11. Ambient temperature
12. Application type – e.g. scrubber, retrofit
13. Location - flow line, well head

6.7.4. Operating Considerations

Rotary drums are simple in concept, however, their operation and maintenance in a gas storage field under dynamic conditions maybe challenging under harsh weather conditions. Consideration should be given to the performance of the device under the following conditions: (1) rapid changes in flow line pressure during withdrawal and injection, (2) rapid changes in liquid amounts, (3) formation of ice and hydrates during extended shut-in periods, (4) bi-directional operation during injection and withdrawal periods, (5) transient performance during start-up and shut-in periods, (7) temperature swings over relatively short time periods, and (8) conditions that may induce abnormal bearing wear.

Typical operation
1. Typical operations
2. Storage field type considerations
3. Well behavior as a function of location and time
4. Produced liquids
5. Field fuel usage
6. Field samples
7. Cycling characteristics
8. Drip monitoring
9. Fluid samples
10. Shut-in considerations
11. Start-up considerations

Separation Efficiency

1. Functions of operating conditions
   a. Water content
   b. Temperature
   c. Pressure
   d. Flow rate
   e. Composition
   f. Flow rate range
   g. Flow regime considerations
   h. Entrained performance vs. slugging performance
   i. Liquid hold-up
   j. Reverse flow considerations

2. Time of year
   a. Withdrawal season
   b. Injection season
   c. In-season cycling
   d. Liquid transport in the flow lines

3. Cost considerations
   a. Equipment
   b. Installation
   c. Operation
   d. Maintenance
   e. Retrofitting

6.7.5. Maintenance Considerations

1. Maintenance and support scheduling requirements are relative to other field operating requirements.
2. Daily inspection and visual for rotation and process operation.
4. At 720 hours of operation it is a check of the rotation speed versus flow to look for changes in performance indicating mechanical wear or bearing damage.

5. At 8000 hours it should be disassembled and inspected for rotation wear. Full visual inspection of housing, clean-out accumulated solids, full bearing replacement and/or rebuild, bearing lip seal replacement as required, re-sleeve shaft. Replace batteries on speed indicator.

6. At 32000 hrs. the rotor assembly should be rebalanced. Dismantling is not permitted due to the risk of extensive damage. It will void all warranties and guarantees.
7. Conclusions and Recommendations

Hydrates can be more effectively managed by applying the knowledge obtained:

- from the data and methods referred to in this report,
- low cost flow monitoring and flow control equipment,
- accurate liquid water and hydrate inhibitor monitoring,
- reliable fluid sweeping and flow control,
- and industry experience with hydrate problems.

The experimental data show that by utilizing flow monitoring in the storage field, i.e. more temperature, pressure, and flow rate measurements is an important key to controlling hydrate formation, deposition, constriction and blockage development. The storage fields in this study did not have adequate sensors installed to be able to detect risky operating conditions or when hydrate problem may be developing.

In addition to the sensors, it is important to obtain real-time updates of the flow that are provided to field personnel. The data in this report shows that hydrate blockages can develop very quickly. Robust communication to the field sites is important.

7.1. Water Control

The fundamental ingredients for hydrate formation are water, natural gas, temperature and pressure. Knowing the amount of water and controlling it is the most important element required to control hydrates. Removing through separation, limiting, or controlling the source of the problem, in terms of the amount of water reaching the flow lines, is an effective means to deter hydrate constrictions and hydrate blockage development. Coupling this approach with strategic methanol washes should keep flow lines functioning properly.

Current technology in the field requires personnel to be vigilant and continually blow down drips and monitor the amount of free liquid produced by the well. This is not always possible due to the demands placed on field personnel, hence automating water monitoring, water dumping, measuring free and condensed water production, and water control is a critical to hydrate control in the gas storage field.

7.2. Temperature Control
The hydrate phase diagrams show that hydrate problems can be reduced by increasing the temperature in the flow lines. Most storage fields do not have temperature transmitters adequately installed. Temperature should be measured and monitored throughout the flow lines, both surface and subsurface. The temperature data should be automatically acquired and transmitted to the field operators. It should then be posted on a hydrate phase diagram along with the amount of water that is estimated to be present in the flow lines at a particular location.

Secondly, temperature is also important for monitoring the saturation conditions of the gas phase in the surface and subsurface flow lines. Dry gas will reduce the amount of free water and methanol in the flow lines.

Lastly, temperature considerations are important for valves and expansion devices due to the Joule-Thomson cooling that occurs in the expansion process. Cooling curves can be superimposed on the hydrate phase diagram to identify potential hydrate formation problems. Heaters or methanol injection can be installed at these locations to mitigate hydrate problems caused by cooling of the gas and any associated condensation.

7.3. Pressure

In parallel with temperature probes, pressure and differential pressure sensors are critical for hydrate control. Gas storage fields do not have adequate pressure sensors for real-time hydrate control monitoring.

7.4. Inhibitor Control

Hydrates will likely present in many flow lines due to the condition of the gas from the storage well or flow line and the operating temperature and pressure conditions. This is likely the case in many storage fields. The presence of hydrates does not mean a flow blockage is imminent, rather, it means that the particular location is operating in a blockage risk zone. Hence it is susceptible to hydrates being transported by the flow to regions in the flow that will induce a blockage to develop.

When hydrate problems occur methanol is currently the most effective hydrate inhibitor in use in the gas storage field. The use of methanol needs to be tailored to the actual amount of water that is being produced or is in place in the flow line in order for the methanol to provide an effective hydrate control.

The amount (mass) of methanol that is required is directly related to amount (mass) of water and the storage field well and flow-line operating conditions. Again, monitoring the free water production in the flow lines is important to optimizing and controlling the use of methanol.
In addition, methanol needs to be used in a pre-emptive manner during shut-in and start-up operations at problem locations. A slug should be delivered into the flow line at the appropriate location prior to shut-in. This will prevent hydrate formation and dissolve or reduce any residual hydrates in the flow line as the gas equilibrates to the ambient conditions in the flow line.

Prior to start-up a slug of methanol should be delivered in a manner that creates annular flow of the methanol when flow is restarted. The annular flow regime will help to distribute the methanol along the walls of the pipe. This will facilitate decomposing hydrates that remain on the pipe wall.

As shown by the hydrate video data, this procedure flushes and dissolve hydrates off of the flow line walls and clears the pipe of any residual hydrates. Methanol slug injection should be automated for locations that are prone to hydrate problems.

7.5. Flow Velocity Control

The practice of over-sizing flow lines needs to be avoided. Overdesign and oversizing flow lines cause substantial quantities of liquid to be held-up in the flow lines. Low liquid velocities promote hydrate formation. Low velocities cannot adequately transport liquid held-up in the pipe to locations where hydrates are less of a problem to manage.

Flow velocity can be an effective means to sweep the pipe of liquids. Empirical data suggests that a flow velocity of four ft./sec. can effectively sweep liquids in the flow line. In storage field flow lines with hydrates, the CEESI data indicate that velocities exceeding seven ft./sec. rapidly transports hydrates downstream.

High gas velocities carry liquids and unagglomerated hydrates downstream to locations where the liquid problem may handled by separators.

Sweeping the lines with high velocity flow can be accomplished by inducing flow transients at specific locations in the flow lines. Coupling this with methanol injection can be an effective approach to consider for clearing flow lines of water and hydrates.

7.6. Flow Line Maintenance

The ability to maintain the condition of the flow lines is critical to avoiding hydrate constrictions and flow blockages. The experimental findings from this study strongly suggest that hydrates will be found throughout the storage field flow lines. Real-time monitoring and maintenance, i.e. of the flow lines is critical.
7.7. **Field Equipment Suggestions**

The following field equipment items are needed to help monitor the condition of the gas and liquids in flow lines in gas storage field flow lines.

- Temperature monitoring is important for the field operators to know so they understand the state condition of the fluids in their flow lines and know the amount of methanol that must be injected in order to minimize hydrate problems. Temperature probes should be flush with the pipe to minimize hydrate problems with the probe.

- Real-time liquid water measurement is needed beginning at the well-head. This will provide an improved knowledge of the free liquids in the flow system. In addition it is needed to optimize the injection of methanol relative to the free water that is produced in the system.

- Reliable gas phase water monitors. In addition to free water, water will condense from the gas phase and accumulate on the flow line walls over time depending on the operating conditions. This is required to determine the amount of methanol to inject relative to the condensed water phase.

- More reliable data acquisition and communication systems relative to flow reliability monitoring, i.e. a short enough sampling interval to permit the tracking and correction of any hydrate problems.

- Improved methanol injection system. Current methanol systems drip methanol into the flow lines. The systems are not operated in a manner to wash the flow line walls. Hence hydrates continue to build up on the walls of the pipe.

- Low cost compact separator that limits the amount of water in the flow lines and is convenient for field personnel to maintain under the harshest operating conditions.

7.8. **Research Needs**

This work has opened up significant opportunities to obtain hydrate flow data that delineates the dynamics of fluid flow and hydrate aggregation dynamics. Such data is critical to making real progress on hydrate control that can be translated into field useable technologies.

Additional data needs that have been identified by this project include the following sets of data that should be considered for additional improvements hydrate control.
Additional hydrate tests should include:

1) free liquid measurement at the well-head,
2) down-hole hydrate tests,
3) hydrate flow behavior in a network,
4) high velocity hydrate flow data.

Figure 112. Hydrates recovered from the Greenlick storage field, courtesy of Dominion

Considerable experience has been acquired working with gas hydrates in the field and in the flow laboratory. The hydrate flow test facility is unique. The hydrate flow data that have been acquired are unique and represent a step towards building a comprehensive understanding of complex hydrate flow behavior in flow lines. An extensive video library has been constructed of the measured hydrate flow data. The CEESI hydrate flow data are phenomenological data that have been obtained under specific flow conditions that have helped elucidate hydrate blockage development problems in gas storage fields. The data show the dynamic nature of hydrate transport, deposition and blockage development in flow lines. Hydrate flow data need to be expanded in a systematic manner beyond those conditions that occur in gas storage fields. As wells mature, and water production increases, there will be an increasing need to identify the most reliable low cost option for monitoring, controlling and operating with hydrates in flow lines.

The following summarizes the experience and some needs for future hydrate flow studies:
1) Hydrate flow is complex and very dynamic. Hydrate behavior in the flow lines depends on the specific fluids present, i.e., water, condensate, and oils and is driven by the range of flow velocities encountered in the flow line.

2) Inhibitor amounts must be tailored to the amount of fluid in the flow line and the operating characteristics.

3) Hydrate blockages create high risks for flow-line equipment and field personnel.

4) The less equipment on the flow line, the less likelihood hydrates will agglomerate and impede flow and destroy instrumentation.

5) Simple, non-intrusive, inexpensive hydrate monitoring equipment is needed for gas storage fields.

6) Compact separators at the wellhead need to provide deep separation.

7) Hydrate formation and transport studies in wet gas and multiphase flow meters is needed.

8) Operating practices need to investigate how to reduce the likelihood of hydrate blockages during transient flow conditions.

9) Gas storage field data acquisition and communication for hydrate control needs to be improved for gas storage field operators.

10) The performance of advanced hydrate inhibitors and inhibitor cocktails under full-scale flow test conditions must be systematically investigated. The flow data suggest that there are likely problems in certain flow regimes with advanced inhibition strategies.

11) Hydrate flow data are needed for a range of liquid loading and gas velocities. The fluids should include water and condensates, and include studies with different types of hydrate control chemicals.
References:

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8. Appendix – Hydrate P-T diagrams for Various Gas Storage Fields

Figure 113. Hydrate P-T formation conditions, 3Q03, Greenlick
Figure 114. Hydrate P-T formation conditions, 1Q04, Greenlick
Figure 115. Hydrate P-T formation conditions, 2Q04, Greenlick

Operating Risk Curve
Hydrate Freeze (High Pressure Range)
Dominion, 2Q04, Greenlick

Temperature (Deg.F)
Pressure (psia)

Figure 116. Hydrate P-T formation conditions, 3Q04, Greenlick

Operating Risk Curve
Hydrate Freeze (High Pressure Range)
Dominion, 3Q04, Greenlick

Temperature (Deg.F)
Pressure (psia)
Figure 117. Hydrate P-T formation conditions, 4Q04, Greenlick

Operating Risk Curve
Hydrate Freeze (High Pressure Range)
Dominion, 4Q04, Greenlick

Figure 118. Hydrate P-T formation conditions, 1Q05, Greenlick

Operating Risk Curve
Hydrate Freeze (High Pressure Range)
Dominion, 1Q05, Greenlick
Figure 119. Hydrate P-T formation conditions, 2Q05, Greenlick

Operating Risk Curve
Hydrate Freeze (High Pressure Range)
Dominion, 2Q05, Greenlick

Figure 120. Hydrate P-T formation conditions, 3Q05, Greenlick
Figure 121. Hydrate P-T formation conditions, Loreed, 1104

OPERATING RISK CURVE
HYDRATE FREEZE (Moderate Pressure Range)
El Paso, Michigan, Loreed_1104

Figure 122. Hydrate P-T formation conditions, Loreed, 0105

OPERATING RISK CURVE
HYDRATE FREEZE (Moderate Pressure Range)
El Paso, Michigan, Loreed_0105
Figure 123. Hydrate P-T formation conditions, Loreed, 0305

OPERATING RISK CURVE
HYDRATE FREEZE (Moderate Pressure Range)
El Paso, Michigan, Loreed_0305

Figure 124. Hydrate P-T formation conditions Reed City, 0205

OPERATING RISK CURVE
HYDRATE FREEZE (Low Pressure Range)
El Paso, Michigan, Reed City_0205
Figure 125. Hydrate P-T formation conditions, Eaton Rapids, 0205

OPERATING RISK CURVE
HYDRATE FREEZE (Moderate Pressure Range)
El Paso, Michigan, Eaton Rapids_0205

Figure 126. Hydrate P-T formation conditions, South Chester, 0205

OPERATING RISK CURVE
HYDRATE FREEZE (Moderate Pressure Range)
El Paso, Michigan, South Chester_0205
Figure 127. Hydrate P-T formation conditions, Blue Lake, 0105

OPERATING RISK CURVE
HYDRATE FREEZE (Moderate Pressure Range)
El Paso, Michigan, Blue Lake_0105

Figure 128. Hydrate P-T formation conditions, Loreed, 1104

OPERATING RISK CURVE (HIGH PRESSURE)
HYDRATE FREEZE
El Paso, Michigan, Loreed_1104
Figure 129. Hydrate P-T formation conditions, Loreed, 0105

OPERATING RISK CURVE (HIGH PRESSURE)
HYDRATE FREEZE
El Paso, Michigan, Loreed_0105

Figure 130. Hydrate P-T formation conditions, Loreed, 0305

OPERATING RISK CURVE (HIGH PRESSURE)
HYDRATE FREEZE
El Paso, Michigan, Loreed_0305
Figure 131. Hydrate P-T formation conditions, Reed City, 0205

OPERATING RISK CURVE (HIGH PRESSURE)

HYDRATE FREEZE

El Paso, Michigan, Reed City_0205

Figure 132. Hydrate P-T formation conditions, Eaton Rapids, 0205

OPERATING RISK CURVE (HIGH PRESSURE)

HYDRATE FREEZE

El Paso, Michigan, Eaton Rapids_0205

Temperature, °F

Pressure, psia

50 55 60 65 70 75 80

1000 1200 1400 1600 1800 2000 2200 2400 2600 2800 3000 3200 3400 3600

50 55 60 65 70 75 80

1000 1200 1400 1600 1800 2000 2200 2400 2600 2800 3000 3200 3400 3600
Figure 133. Hydrate P-T formation conditions, South Chester, 0205

OPERATING RISK CURVE
HYDRATE FREEZE (HIGH PRESSURE)
El Paso, Michigan, South Chester_0205

Figure 134. Hydrate P-T formation conditions, Blue Lake, 0105

OPERATING RISK CURVE
HYDRATE FREEZE (HIGH PRESSURE)
El Paso, Michigan, Blue Lake_0105
Figure 135. Hydrate P-T formation conditions, Nat.Fuels, Summit, E04A

OPERATING RISK CURVE
HYDRATE FREEZE
National Fuel Gas, Summit, E04A

Figure 136. Hydrate P-T formation conditions, Nat.Fuels, Summit, E04B

OPERATING RISK CURVE
HYDRATE FREEZE
National Fuel Gas, Corry, E04B
Figure 137. Hydrate P-T formation conditions, Nat.Fuels, Keeler, E07A

OPERATING RISK CURVE
HYDRATE FREEZE
National Fuel Gas, Keeler, E07A

Figure 138. Hydrate P-T formation conditions, Nat.Fuels, East Branch, E07B

OPERATING RISK CURVE
HYDRATE FREEZE
National Fuel Gas, East Branch A, E07B
Figure 139. Hydrate P-T formation conditions, Nat.Fuels, East Branch, E07C

OPERATING RISK CURVE
HYDRATE FREEZE
National Fuel Gas, East Branch B, E07C

Figure 140. Hydrate P-T formation conditions, Nat.Fuels, Collins, E08A

OPERATING RISK CURVE
HYDRATE FREEZE
National Fuel Gas, Collins, E08A
Figure 141. Hydrate P-T formation conditions, Nat.Fuels, Lawtons, E08B

OPERATING RISK CURVE
HYDRATE FREEZE
National Fuel Gas, Lawtons, E08B

Temperature, °F
Pressure, psia

Figure 142. Hydrate P-T formation conditions, Nat.Fuels, Zoar, E08C

OPERATING RISK CURVE
HYDRATE FREEZE
National Fuel Gas, Zoar, E08C

Temperature, °F
Pressure, psia
Figure 143. Hydrate P-T formation conditions, Nat.Fuels, Nashville, E10C

OPERATING RISK CURVE
HYDRATE FREEZE
National Fuel Gas, Nashville, E10C

Figure 144. Hydrate P-T formation conditions, Nat.Fuels, Perrysburg, E10D

OPERATING RISK CURVE
HYDRATE FREEZE
National Fuel Gas, Perrysburg, E10D
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