Final Report to

Deepwater Reverse-Circulation Primary Cementing
10121-4502-01.FINAL

Deepwater Reverse-Circulation Primary Cementing
10121-4502-01

September 21, 2014

Jeff Watters, Principal Investigator

General Manager
CSI Technologies
2202 Oil Center Court
Houston TX, 77073
www.csi-tech.net

LEGAL NOTICE

This report was prepared by CSI Technologies, LLC as an account of work sponsored by the Research Partnership to Secure Energy for America, RPSEA. Neither RPSEA members of RPSEA, the National Energy Technology Laboratory, the U.S. Department of Energy, nor any person acting on behalf of any of the entities:

a. **MAKES ANY WARRANTY OR REPRESENTATION, EXPRESS OR IMPLIED WITH RESPECT TO ACCURACY, COMPLETENESS, OR USEFULNESS OF THE INFORMATION CONTAINED IN THIS DOCUMENT, OR THAT THE USE OF ANY INFORMATION, APPARATUS, METHOD, OR PROCESS DISCLOSED IN THIS DOCUMENT MAY NOT INFRINGE PRIVATELY OWNED RIGHTS, OR**

b. **ASSUMES ANY LIABILITY WITH RESPECT TO THE USE OF, OR FOR ANY AND ALL DAMAGES RESULTING FROM THE USE OF, ANY INFORMATION, APPARATUS, METHOD, OR PROCESS DISCLOSED IN THIS DOCUMENT.**

THIS IS A FINAL REPORT. THE DATA, CALCULATIONS, INFORMATION, CONCLUSIONS, AND/OR RECOMMENDATIONS REPORTED HEREIN ARE THE PROPERTY OF THE U.S. DEPARTMENT OF ENERGY.

REFERENCE TO TRADE NAMES OR SPECIFIC COMMERCIAL PRODUCTS, COMMODITIES, OR SERVICES IN THIS REPORT DOES NOT REPRESENT OR CONSTIITUTE AND ENDORSEMENT, RECOMMENDATION, OR FAVORING BY RPSEA OR ITS CONTRACTORS OF THE SPECIFIC COMMERCIAL PRODUCT, COMMODITY, OR SERVICE.

Abstract

In Reverse-Circulation Primary Cementing (RCPC) fluids are pumped downhole via the annulus and then up into the casing, in contrast to a conventional cement job where fluids are pumped down the casing then up into the annulus. The objective of the RPSEA Deepwater Reverse-Circulation Primary Cementing (RCPC) project is to assess the viability of performing RCPC to reduce circulation pressure requirements for deepwater wells, to determine required technology to apply RCPC for deepwater wells, and to present development strategies for required technologies. This report is submitted in fulfillment of Task 19 of the Deepwater Reverse-Circulation Primary Cementing project and contains a summary of Phase I and II activities.

Signature and Date Stamp

X

Jeff Watters Date
Principal Investigator

THIS PAGE INTENTIONALLY LEFT BLANK

Acknowledgement Statement

CSI Technologies wishes to acknowledge the support of RPSEA, Weatherford and the University of Houston, as well as the Working Project Group for their invaluable expertise. Working Project Group members include Anadarko, BP, Chevron, Conoco Phillips, Hess, Schlumberger and Shell.

Funding for the project is provided through the “Ultra-Deepwater and Unconventional Natural Gas and Other Petroleum Resources Research and Development Program” authorized by the Energy Policy Act of 2005. This program—funded from lease bonuses and royalties paid by industry to produce oil and gas on federal lands—is designed to assess and mitigate risk enhancing the environmental sustainability of oil and gas exploration and production activities. RPSEA is under contract with the U.S. Department of Energy’s National Energy Technology Laboratory to administer three areas of research. RPSEA is a 501(c)(3) nonprofit consortium with more than 180 members, including 24 of the nation's premier research universities, five national laboratories, other major research institutions, large and small energy producers and energy consumers. The mission of RPSEA, headquartered in Sugar Land, Texas, is to provide a stewardship role in ensuring the focused research, development and deployment of safe and environmentally responsible technology that can effectively deliver hydrocarbons from domestic resources to the citizens of the United States. Additional information can be found at www.rpsea.org.

Nomenclature:

API: American Petroleum Institute

BBL: Barrel

BDF: Backward Difference Formula

BH: Bottom Hole

BHCT: Bottom Hole Circulating Temperature

BHP: Bottom Hole Pressure

BHST: Bottom Hole Static Temperature

BOP: Blow Out Preventer

BPM: Barrels per minute

BWOC: By weight of cement

BWOW: By weight of water

DST: Drill Stem Test

ECD: Equivalent Circulating Density

FEA: Finite Element Analysis

FEM: Finite Element Method

HEC: Hydroxyethyl Cellulose

HS&E: Health, Safety and Environment

HTHP: High Temperature High Pressure

ID: Inner Diameter

RKB: Rig Kelly Bushing

MD: Measured Depth

MWD: Measurements while Drilling

OBM: Oil Based Mud

OD: Outer Diameter

PBR: Polished Bore Receptacle

PPG: Pounds per gallon

PSI: Pounds per Square Inch

Pv: Plastic Viscosity

RCPC: Reverse-Circulation Primary Cementing

RFID: Radio Frequency Identification

RP/GS: Rotating Paddle Gel Strength

SBM: Synthetic Based Mud

TD: Total Depth

TOC: Top of Cement

TOL: Top of Liner

TVD: Total Vertical Depth

UCA: Ultrasonic Cement Analyzer

UDW: Ultra-Deep Water

WBM: Water Based Mud

WOC: Wait on Cement

Yp: Yield Point

List of Figures

List of Tables

Table of Contents

1

1 Executive Summary

The objective of the RPSEA Deepwater Reverse-Circulation Primary Cementing (RCPC) project is to assess the viability of performing RCPC to reduce circulation pressure requirements for deepwater wells, to determine required technology to apply RCPC for deepwater wells, and to present development strategies for required technologies. In RCPC fluids are pumped downhole via the annulus and then up into the casing, in contrast to a conventional cement job where fluids are pumped down the casing then up into the annulus. The application of RCPC to deepwater wells is expected to reduce bottomhole circulating pressures and prevent lost circulation during cementing as well as increase safety, enhance environmental sustainability, provide zonal isolation, and improve cement seals. Other benefits that have been seen through the application of RCPC include reduced placement time, reduced excess pumped and a reduction in the amount of retarding additives used in the cement.

Challenges in applying RCPC to deepwater include the necessity of a downhole crossover tool to divert fluids into the annulus downhole below the BOP stack, the availability of specialized float equipment, the availability of simulators that are able to model the complex flow path of deepwater RCPC circulation, and cementing fluid design considerations. The approach to this project was divided into two phases and the scope of work comprised analyzing the RCPC placement method, preparing a development path for technology required to apply RCPC to deepwater wells, and creating preliminary operational procedures with associated contingency plans. The objectives of Phase I were to confirm, evaluate and address expected challenges and benefits of RCPC in deepwater. Phase I results were analyzed to determine technical issues and to identify technologies to be developed for implementation of deepwater RCPC. Phase II of the Deepwater RCPC project focused on a more detailed analysis of deepwater RCPC technical requirements and the development of finite-element simulations.

During the course of this project, finite-element software package has been used to develop a robust model capable of handling deepwater RCPC. Also, a method was developed to be able to use workarounds within commercial cementing simulation software to perform deepwater RCPC simulations. The resulting temperature and pressure profiles provided basic estimates of placement. Laboratory intermixing studies have shown that rheology is a key parameter in fluid design and placement while use of a conventional fluid hierarchy can result in interface instability and fluid swapping. Key mechanical components required to perform deepwater RCPC were analyzed to determine the current state-of-the-art, as well as future, performance requirements.

Overall, the applicability and benefits of RCPC to deepwater should be evaluated on a case-by-case basis. Existing gravel pack and sting-in float technology can be modified for use in the near future. However, technology needed for future development includes the modification of float equipment and a switchable crossover that will divert fluids on demand. The next step in tool development should add capabilities that allow for nonmechanical operation of tools from the surface by incorporating technologies such as RFID, chemical-activated triggers, or mud-pressure pulses. Mud removal and fluid separation will remain a major challenge for deepwater RCPC since physical separation will need to be maintained through the use of viscous plugs instead of traditional plugs, darts, or balls. The design methodology of cementing fluids is affected by this change in placement method since the leading edge of cement will become the critical shoe slurry. A close review of simulations of various wells and casing strings reveals that cement slurry is often exposed to a higher downhole circulating temperature, and that placement time can be shortened significantly in some cases. Hydraulic analysis of these deepwater strings has confirmed the critical depths at which placement by RCPC results in a lower equivalent circulating density (ECD).

2 Project Introduction

2.1 RCPC Background Information

In Reverse-Circulation Primary Cementing (RCPC) fluids are pumped downhole via the annulus and then up into the casing, in contrast to a conventional cement job where fluids are pumped down the casing then up into the annulus. RCPC has been in use as a placement technique since the 1960's. Applications have included casing leak repair, tiebacks, and production casing. Reverse cementing has also been used in geothermal wells with foamed cement due to low formation fracture pressure and a high risk of lost circulation. Most previous published applications have been on land wells, but RCPC has also been implemented offshore in shallow water wells. The primary benefits that have been seen with cementing through reverse circulation is that friction pressures and equivalent circulating densities (ECD) are reduced since it is no longer necessary to lift fluids all the way up the annulus as during conventional cementing placement. Gravity also helps to place the fluids down the annulus. Other benefits that have been seen through the application of RCPC include reduced placement time, reduced excess pumped and a reduction in the amount of retarding additives used in the cement. Keeping placement pressures low is critical in formations with low fracture gradients or where lost circulation is a concern. Deepwater wells continue to be drilled deeper in challenging conditions, with increasingly complex architecture. These deepwater wells will need to be effectively cemented and sealed to ensure zonal isolation for production efficiency and environmental protection. A placement technique that can potentially reduce lost circulation risk, reduce ECDs and lower friction pressures in formations with a narrow pore-frac gradient has a clear appeal to the deepwater industry. However, since a reverse-circulation placement technique has not yet been implemented in deepwater, the potential benefits and risks will need to be thoroughly evaluated prior to implementation.

2.2 Project Challenges

An example of a deepwater RCPC configuration for a liner is shown in Figure 1 (a), compared to a conventional flow path shown in Figure 1 (b). In land-based RCPC operation, fluids were injected directly into the annulus. For deepwater RCPC placement to occur, fluid will need to be pumped down a workstring so that no cementing fluids are pumped in the riser, then through a crossover tool to be diverted into the annulus. Fluids will continue to circulate down the annulus, back up into the casing, through the crossover tool and then into the annular space around the work string.

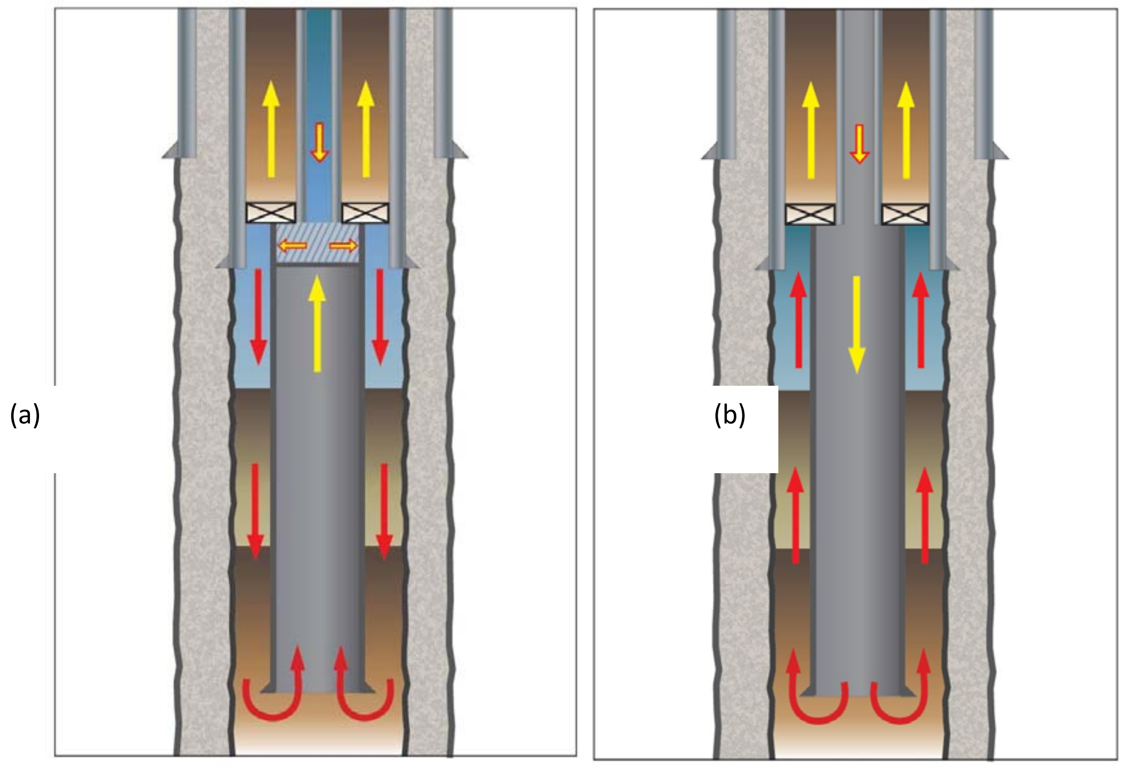


Figure 1: (a) Reverse-Circulation Primary Cementing (b) Conventional Primary Cementing

A review of past literature on the current state-of-the-art of RCPC has shown that the following challenges apply:

- Accurately identifying when cement reaches the casing shoe to avoid incomplete cementation around the shoe or a large amount of cement to drill out from the casing.
  - When cement has filled the shoe track area, pumping can be stopped. If more cement than necessary is pumped the cement left in the casing will need to be drilled out, which increases cost and rig time. However, stopping before the

cement has reached the shoe can result in incomplete cementation around the shoe.

- The availability of specialized float equipment to circulate the well and perform RCPC operations.
  - A challenge with RCPC is that conventional float equipment cannot be used. Past RCPC jobs have used either specialized float equipment, or no float equipment at all. A technique that has been used on land wells is to reverse cement through an inner string without float equipment. A disadvantage of this method is that pressure will need to be held on the casing until the cement sets, which can increase the risk of micro-annulus formation. This technique is unlikely to be used in deepwater. Various patents for specialized float equipment and placement methods for reverse cementing have been established, however viability of the application to deepwater need to be evaluated.
- Cement design modifications due to temperatures variations during placement affecting WOC time and thickening time since cement near the bottom of the annulus is exposed to the Bottom Hole Circulating Temperature (BHCT) while cement near the top of the annulus is exposed to a lower temperature.
  - Cement designs for RCPC are measured by the same test parameters as with conventional cementing, including thickening time, compressive strength development, gel strength development, free fluid, fluid loss and rheology. However, there are some design considerations and modifications that may be made to slurries for RCPC. Considerations include rheological hierarchy, mud removal efficiency, and concentration of cementing additives.
- Computer simulation and modeling are necessary for parameters such as ECD, pump rates, friction pressures, temperature gradient and mud removal efficiency.
  - A challenge in applying RCPC cement designs to deepwater application is the development of software to model and monitor RCPC jobs. Considerations include placement simulations, mud removal, ECD modeling and the temperature gradient as the cement is pumped.

2.3 Project Approach

Phase I of the Deepwater RCPC project has focused on investigating the current status of technologies and documenting those that need to be developed to RCPC for deepwater applications. The objectives of the project tasks in Phase I have been to confirm, evaluate and address expected challenges and benefits of RCPC in deepwater. The first task of the project was to form a Working Project Group consisting of operating companies and service companies. The Working Project Group provides technical guidance on conditions and challenges of deepwater operations and how they would relate to RCPC. Next, an industry-wide survey of experts in the field was conducted. Industry experts in deepwater and experts experience with reverse-circulation placement techniques were surveyed through an online survey. The purpose of this survey was to gather opinions, expectations and concerns about the application of reverse-circulation cementing techniques to deepwater. The information collected in this survey was combined with Working Project Group feedback and information produced from the Technology Status Assessment to guide subsequent tasks.

Two generic deepwater well schematics were used for investigations in subsequent phases of the project. The flow path used for placement analysis was illustrated in Figure 1 (a), where fluids are pumped down the drill pipe below the BOP stack and then diverted into the annulus near the liner or casing hanger through a crossover tool. Another possible path for reverse circulation is down the BOP stack lines and then down the annulus, with returns taken up the drill pipe. However, due to safety considerations the use of this flow path was not considered as an operational possibility for this project. Schematic #1 can be seen in Figure 2 (a). The strings of interest on Schematic #1 (highlighted in yellow) are the 16-in. intermediate liner, the 9⅞-in. intermediate liner, and the 7⅝-in. production liner. Schematic #2 can be seen in Figure 2(b). The strings of interest on Schematic #2 are highlighted in yellow and are the 16-in. intermediate liner, the 13⅝-in. intermediate casing, and the 11⅞-in intermediate liner. Note that the figures are for reference only and are not to scale.

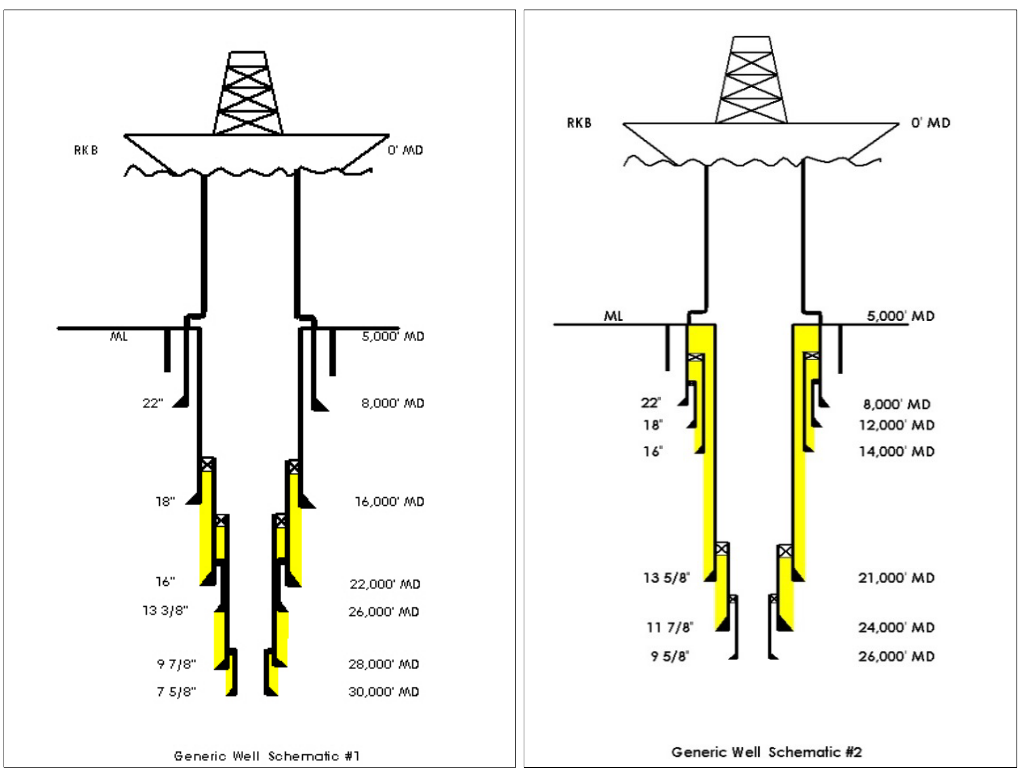


Figure 2: (a) Generic Deepwater Well Schematic #1 (b) Generic Deepwater Well Schematic #2

There were many anticipated challenges to the application of RCPC to deepwater including modeling and simulations, mechanical placement controls, and cementing materials. Subsequent tasks of this project included the development of a series of simulations and numerical models applicable to RCPC operations in deepwater including finite element modeling, temperature simulations, and job placement simulations. The evaluation and analysis of this task was performed by the University of Houston and by CSI Technologies. Mechanical components required to implement RCPC in deepwater wells were also investigated and analyzed. This evaluation was performed by Weatherford, and included analysis of cement flow and placement controls required to direct fluid down an annulus of a deepwater well casing or liner, and a means to separate fluids during placement. Cementing material considerations were also studied to identify potential design and performance benefits and issues based on cement performance under deepwater conditions when placed by RCPC. Considerations included fluid intermixing, key aspects of spacer design, additive sensitivity, and wait-on-cement (WOC) time. This analysis and evaluation was conducted by CSI Technologies.

Operational performance of RCPC in deepwater was another key aspect investigated in Phase I. While some operational procedures will remain the same as with conventional placement, the application of a novel technique will require special consideration and planning. This included the identification and addressing of expected issues that come from the application of the RCPC process on a deepwater rig. Anticipated issues included liquid additive proportioning for accurate cement formulation, mixing rates and cement deliverability, measurement of displacement volumes and measurement of downhole and return flow rates. Overall, it was expected that there would be numerous technical issues that must be addressed before routine RCPC operations can occur in deepwater wells. Phase I results have been analyzed to determine technical issues and to identify technologies to be developed for implementation of deepwater RCPC.

Phase II of the Deepwater RCPC project focused on a more detailed analysis of deepwater RCPC technical requirements and the development of the COMSOL simulations. Preliminary models developed in Phase I were refined and developed in more detail, with a focus on ECDs and pressures during placement. Also, workarounds for RCPC in commercial software were further investigated. Next were comparisons of results from both the COMSOL model and the commercial simulators on temperatures and pressures. Phase II work on the mechanical placement controls also built on Phase I results. Since the development of a switchable crossover tool was identified as a development area in Phase I, Phase II analysis included tool requirements for long strings and tie-back strings. Further analysis was conducted specifically for crossover tool applications in conjunction with a liner hanger. Areas of interest were ways to combine the crossover tool with the liner hanger assembly, compatibility with existing liner hangers and tools, and operations with both set and unset liner hangers. Since the selection and use of float equipment would need to be determined on a case by case basis, further study was done on methods to control fill-up and flow back and minimizing flow restrictions during placement.

Phase II work also included the design optimization of cement and spacer design based on the fluid intermixing studies conducted in Phase I. Other considerations were that slurries for RCPC applications will typically not be exposed to the same circulating temperature as those during conventional placement. The performance of optimized RCPC cement designs were compared with conventional designs, with thickening time, compressive strength development, gel strength development, stability and fluid loss as areas of focus. Another area of fluid optimization looked at the design and use of viscous pills for downhole fluid separation as an alternative to mechanical separation; balls and wiper darts could be used in the work string section only. Phase II tasks also included the preparation of an operational plan to successfully implement RCPC in deepwater and a contingency plan for all major expected contingency situations.

3 Phase 1 Summary and Conclusions

Phase I results indicate that it was necessary to continue the initial deepwater RCPC study in more detail to evaluate the effects of real-well conditions and variables on RCPC viability, with Phase II focusing on a more detailed analysis of deepwater RCPC requirements and the development of operational RCPC plans under real-well scenarios. A planned focus of Phase 2 was improvement of the FEM model developed for this project, and on the crossover tool needed to divert flow during placement. In the model, temperatures and equivalent circulating densities have been predicted; however, there were a number of additional features necessary to more realistically predict the deepwater reverse cementing process. Also, further investigation was needed on specific operational modeling for RCPC operations and contingencies, including identification of major equipment, software, placement design and techniques in detail.

In Phase 1, the following development areas were identified:

Mechanical Placement Controls

- One of the biggest project challenges from the mechanical side will be the development of a switchable crossover. The crossover needs three positions: 1) going in the hole with flow directed in the conventional direction through the ID of the casing; 2) switched to direct flow to the annulus side of the casing while allowing returns to come through the ID of the casing then exit to the annulus above a pack off above the reverse flow port; 3) switch back to allow flow to go in the conventional direction to set the liner hanger and possible activate a shut off valve to keep cement in place while pulling the work string out of the hole.

- Further study is needed for float equipment. Float equipment to keep cement in place on the back side of the casing needs to be decided upon on a case by case basis at this juncture of reverse cementing.

Modeling and Simulations

- Due to the specific nature of the wells under consideration, standard commercially available software packages are unable to model the flow path through the complex configuration of a deepwater reverse-circulation cementing process. Further refinement and analysis is needed to evaluate downhole pressures and temperatures in a full-scale well.

- A COMSOL Multiphysics finite-element software package has been used to develop a robust model capable of handling the reverse-circulation cementing process. The model has been successfully applied to a scale well to predict temperatures and pressures, and work is currently being performed to scale the model to the full-size wells. Once the full-size simulations are complete, comparisons with commercial software simulation results are needed to evaluate the applicability of the commercially-available software to deepater RCPC operations.

Cementing Materials

- Fluid intermixing is dependent on fluid rheology, fluid density, well geometry and flow rates. These properties affect the design of both slurries and spacers. In Phase I, rheological and density hierarchy effects were investigated. Further investigation is needed on the effects of well geometry, eccentricity and deviation, as well as the quantification of these effects in order to provide best practices for RCPC fluid design.

Operational Considerations

- Many operational considerations are expected to remain the same with RCPC as with a conventional deepwater primary cementing. However, there are many anticipated additional considerations introduced by RCPC.

- Considerations that need further study include hole cleaning, circulation direction, mixing rates, measurement of displacement volumes and measurement of downhole and return flow rates.

- Additional considerations specifically for deviated wells need to be investigated.

4 Phase 2 Summary and Conclusions

Overall, the applicability and benefits of RCPC to deepwater wells should be evaluated on an individual basis. In some cases, RCPC can significantly shorten operational time for cement placement. Simulations and determination of the critical depth can determine if RCPC is viable for that string since in RCPC can result in an ECD reduction during placement. Weak formation or zone needs to be below the critical depth for RCPC to have an advantage

Mechanical Placement Controls

- A switchable crossover is preferred to give flexibility in desired flow direction during various operations ranging from running casing, cement placement and setting liners.

- A mechanically operated crossover, which could be a modification of a gravel pack crossover, may be the first to market for reverse cementing.

- A crossover tool that is strictly operated with ball(s) and/or dart(s) would be a major challenge.

- A crossover tool can be located above the liner/casing hanger, or below the hanger if port collars are used.

- From an operator's perspective the selection and placement of floating equipment for reverse cementing should be done on a well by well basis.

- The float equipment can be run near the top of the liner and held open by a stinger, or near the bottom of the casing if needed to aid flow into the casing ID.

- Various methods could be used to detect the location of fluids downhole or trigger the operation of downhole crossover tools or valves. These methods include balls, darts, RFID tags, chemical tags, mud pressure pulse, wire drill pipe, hydraulic control lines from the surface, mechanical or gas powered springs, or any combination.

Modeling and Simulations

- A method was developed to be able to use workarounds within commercial cementing simulation software to perform deepwater RCPC simulations. The resulting temperature and pressure profiles are somewhat simplistic.

- A robust model has been developed which predicts temperatures and pressures/ECDs during a RCPC job. This model is built on the COMSOL Multiphysics software package, and uses Finite Element Analysis to simultaneously solve the heat equation and Navier-Stokes equations.

- In the developed model, secondary calculations such as the load on the pump, the presence of U-Tubing and the required back-pressure to prevent U-Tubing are available.

- This model was applied to several example cementing jobs, results indicate that overall the bottom-hole circulating temperature is increased significantly in reverse cementing.

- ECDs at bottom-hole are reduced significantly, and ECDs at the previous shoe can either increase or decrease depending on the configuration of the well. RCPC reduces ECDs at bottom-hole by changing the flow path and reducing the frictional component of the pressure at bottom-hole. The static pressure contribution does not change from conventional to reverse.

- The fact that ECDs can be increased at the previous shoe is a significant issue. If the ECD is reduced at bottom-hole and increased at the previous shoe, then there is a point between those two where the pressures in conventional and reverse circulation are equal. The location of this point with respect to a weak zone or zone of interest in the annulus will be a factor in determining if RCPC is advantageous in that particular application.

- If the previous shoe is at the same depth as the crossover tool, then the pressure in RCPC will be higher than for conventional placement. However, if the overlap between the casing being cemented and the previous casing is large enough, such as with a tight liner lap annulus, then the previous shoe could be lower than the critical depth. In such a configuration, the pressure exerted against the formation could be reduced.

Cementing Materials

- Many slurry considerations for RCPC are expected to be similar to conventional deepwater primary cementing slurry considerations.

- Slurry systems can be tailored to optimize compressive strength development. If there is a significant difference between the static temperatures of the top and bottom of the cement column, additive staging with a decrease in retarders in near the top of cement is possible to optimize compressive strength development throughout that interval.

- Alternative density hierarchies are possible with RCPC placement. Fluid placement downhole is assisted by gravity down the annulus. A conventional density hierarchy, where each fluid pumped is progressively heavier than the preceding fluid, can result in fluid swapping and intermixing in the annulus due to the difference in density.

- Rheology is a key parameter in fluid design and placement. As with conventional placement, an increasing rheological hierarchy is needed to assist with fluid displacement.

Operational Considerations

- Equipment type and configuration can be selected based on operator and regulatory needs, and what is most appropriate for the expected well conditions.

- Preparing personnel on location for the reverse operation will be specific to the type of equipment that is used and/or developed for the operation. Possible contingency situations need to be reviewed and plans should be covered as part of personnel training/pre-job procedure.

4.1 Future Recommendations

Mechanical Placement Controls

- For use in the near future, a ball-operated fixed-type crossover will be easiest to bring to market since it requires modifications to existing commercial tools such as gravel packs. However, long-term development should focus on the commercialization of a switchable crossover since this will provide the operator with greater operational flexibility during deepwater RCPC operations, such as the option to rotate casing, place tool above or below the liner hanger, and to avoid landing the casing before cementing.

- Since a crossover tool that is strictly operated with ball(s) and/or dart(s) would be a major challenge, the next step in tool development will be to add capabilities that allow for non-mechanical operation from the surface by incorporating technologies such as RFID, chemical-activated triggers or mud pressure pulses.

- The type of floating equipment used in deepwater RCPC is likely to be floats that are held open by a stinger. Future recommendations are to apply technologies such as RFID or chemical-activated triggers to operate the floats remotely.

- After the crossover tool, the next critical area of development will be to use emerging technology in deepwater such as RFID and fiber-optics to reliably detect the presence of cement inside the casing shoe. This technology should be used in addition to a volumetric method of monitoring fluids in and returns.

Modeling and Simulations

- Placement simulators should be expanded and made available within the industry to model deepwater RCPC flow paths and cement placement.

- Simple equations to estimate the difference in pressure from conventional to reverse have been developed. These can be used as a preliminary evaluation tool for deepwater RCPC to determine if RCPC will be advantageous, and if the resulting ECDs downhole are acceptable.

Cementing Materials

- Fluid designs will need to be tailored for each application dependent on modeling results and desired parameters.

Operational Considerations

- The personnel on location may or may not have previous experience with a reverse cementing operation. The job timing and inherent procedures will have to be clarified prior to the job for optimal performance.

5 Performance Capabilities and Future Requirements

This section details the current "State of development" of deepwater RCPC. Included are the functional requirements and capabilities of each major equipment, software and technique.

5.1 Equipment and tools

Key mechanical components for reverse-circulation operations were analyzed for the following string types:

- Long string – casing typically hung off near the well head
- Liners – casing typically hung off near the end of the previously run casing with a liner hanger
- Tie Back Strings – casing typically hung off near the well head tied back to the PBR of a previously run liner

5.1.1 Analysis of switchable crossover

For deepwater RCPC, a downhole crossover tool is needed to divert flow from the work string into the annulus to be cemented (Figure 3). Phase 1 work on crossover tool design looked at a fixed crossover and a switchable crossover design option. Fixed crossover types are similar to those used on port collars for gravel packing, and may require a second run in hole after the casing has been landed. The fixed crossover tool is then run in on a work string and stung into a reverse-cementing port collar for pumping. After placement the tool and workstring are pulled to close the port and then reversed out. The operation of a fixed-type crossover tool operated by balls is shown in Figure 4. In comparison, a switchable crossover tool may not need the casing to be landed prior to pumping and the flow direction can be changed downhole without additional tool runs.

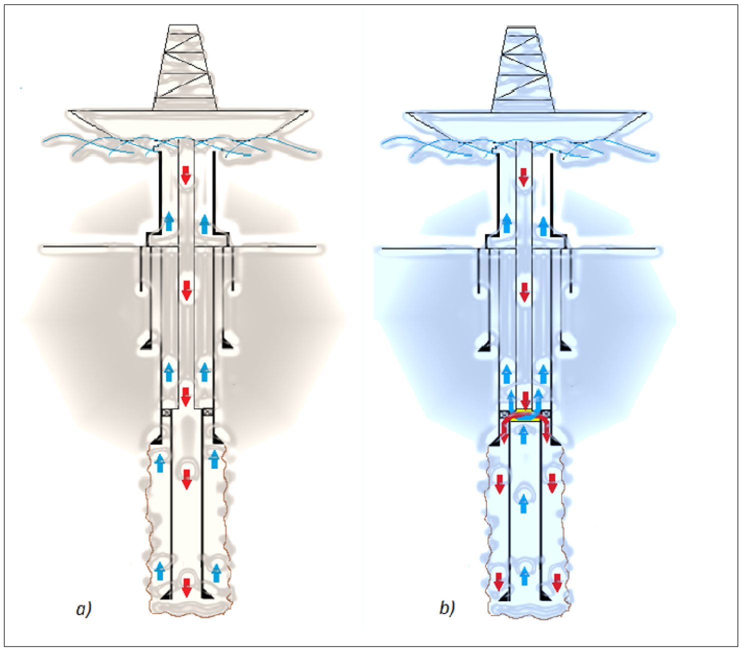


Figure 3: (a) Conventional Flow Path (b) RCPC Flow Path

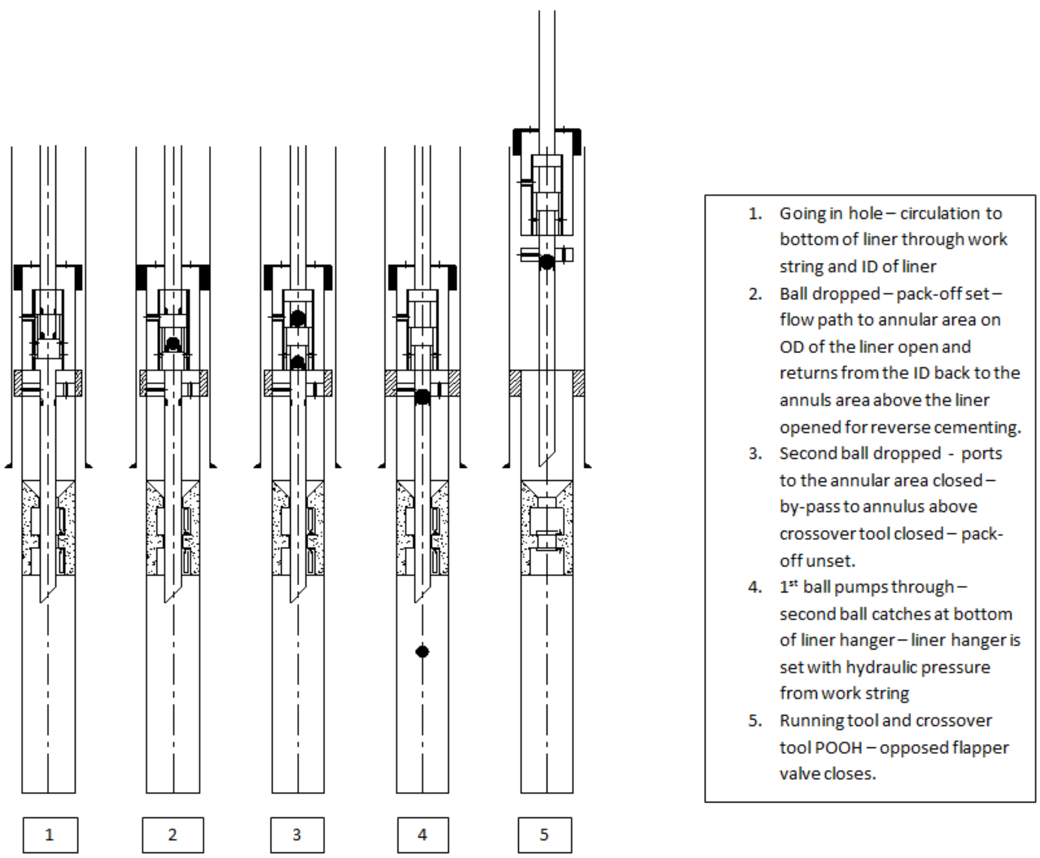


Figure 4: Mechanical Fixed Crossover Tool

The switchable crossover tool located above the top of the liner needs to be compatible with existing liner hangers and casing hangers. It has to allow for the reverse cementing process to take place, before the liner hanger is set or the casing is hung off. The switchable crossover of this design will be discussed further in the next section.

For a switchable crossover type system that uses a port collar located below the liner hanger or casing hanger, then the liner hanger is set or the casing is hung off before the reverse cementing process takes place. This type of placement or reverse cementing operations will require a method to divert flow into the annulus below the liner hanger, such as use of a port collar.[1] Port collars have also been used for cementing operations in relatively weak formations.[2]

5.1.2 Switchable Crossover for Liner Hanger and Casing Hangers

The crossover tool is located above the top of the liner hanger or casing hanger and is intended to be used to place cement on the annulus side of the casing by cementing in the reverse direction before the casing is hung off.

Minimum requirements for the switchable crossover are:

- To be universal, the crossover needs to work with existing liner hangers and/or casing hangers.
- Allow flow in the conventional direction, while the casing is being run into the hole.
- When the casing is at the desired location, the crossover will switch directions so that all the fluids pumped down the work string will be diverted to the annulus between the casing OD and open hole ID with returns being taken up the casing ID and then diverted at the crossover tool to the annular area between the work string OD and previously run casing ID.
- To switch flow directions the crossover must pack-off the annular area between the OD of the tool and the ID of the previously run casing between the exit port from the work sting ID to the exit port from the casing ID.
- After the cement is placed the crossover will then switch back to the conventional direction to allow the liner hanger to be set or the casing hung off. A simple ball and/or dart drop operated crossover can be designed to meet the minimum requirements listed for the crossover tool.

[1] US Patent 7,857,052 "Stage Cementing Methods used in Casing while Drilling" by Giroux, et al, starting with Figure 12A through 12F
[2] Jim McNicol, Archer Oiltools. SPE-168048-MS.

Functional requirements for the crossover tool when located at the top of the casing are:

- Ability to wash/ream the casing to bottom with standard or reverse flow.
    - Reverse flow can be done by pumping down the riser with returns being taken up the liner ID and through the work string ID.
    - Reverse flow can also be done with concentric drill pipe where the fluid is pumped down the outer annulus and returns are taken through the liner ID back up the inner ID of the drill pipe. Note this option pre-supposes a traveling pack-off to keep the fluids separated.
    - Another option is by pumping down the work string with flow crossed over at the crossover tool and returns taken back up the liner ID until the flow is crossed over to the annular area above the crossover tool. Note this option pre-supposes a traveling pack-off to keep the fluids separated.
- Ability of maintaining rotation during washing/reaming in – once the hanger pack-off is set, rotation must stop – the crossover will stay attached to the casing until it's hung off.
- Maintain a minimum ID to allow the dropping of balls and/or darts through the tool(s) when in the conventional circulation mode.
- When used on a casing system that requires a liner hanger, the crossover as a minimum must allow conventional circulation while running in the hole, crossover to reverse cement, and switch back to the conventional flow direction to set the liner hanger.

Desired capabilities for a switchable crossover are to:

- Have a four position crossover tool system that can be switched on demand (Figure 5):

    1. Conventional flow direction where all fluid pumped down the work string goes through the liner ID and back up the annular area between the liner OD and the previously run casing ID or open hole ID. This flow direction also allows fluid flow down the external annulus and back up the liner ID and the work string.

    2. Reverse flow direction where all fluid pumped down the work string is directed to the annular area between the liner casing OD and hole/or previously run casing ID. All returns are taken up the ID of the liner and diverted to the annular area between the work string and previously run casing and riser ID.

    3. Circulation mode where all fluid pumped down the work string is diverted at the tool(s) to the annular area between the working string OD and previously run casing and

riser ID. No fluid enters the liner ID or the annular area between the liner casing and open hole ID. (Needed to place a ball or dart to set a liner hanger, without disturbing the previously placed cement.)

4. Bullhead or Squeeze mode where all fluid pumped into the work string can be used to pressure up the work string to set the liner hanger and operate other tools in the system.

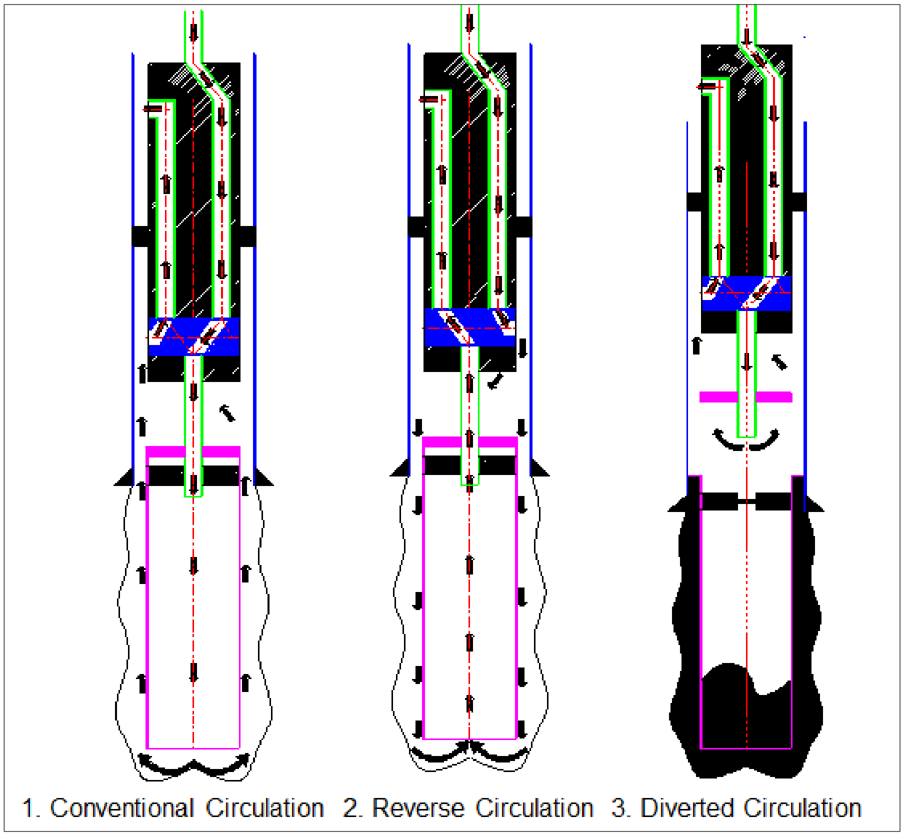


Figure 5: Crossover tool system that is switchable on demand

- Have the ability to send a signal from the surface to the crossover to perform an operation and have feed back to the surface that the operation has been performed in real time. Note: The crossover should allow rotation in all positions. Rotation only needs to stop when the liner hanger is being set.

In reviewing the requirements to the operation mode of the crossover tool, is has been determined that a crossover tool that is strictly operated with ball(s) and/or dart(s) would be a major challenge. To add the desired capabilities to the operating mode of the crossover tool system means that the tool system operating method(s) will need to be evaluated from a multiple discipline stand point. This includes the use of traditional operating systems such as balls and/or darts systems, the use of battery powered systems, surface powered systems (e.g.

hydraulic and/or electrically powered), stored energy systems such as springs – both mechanical and gas powered, or vacuum chamber powered systems that's activated by various methods such as dropped balls, pump down darts, RFID tags, chemical tags, wired drill pipe, a wire line plug in run from the surface, fiber optics, mud pulse, mud pressure pulse, timers, hydraulic lines run from the surface, concentric drill string with the outer annulus of the drill pipe used as a hydraulic fluid carrier, etc. have all been considered. The feasibility of each system or combination(s) of each system will need to be carefully evaluated.

In summary, a mechanically operated crossover, which could be a modification of a gravel pack crossover, may be the first to market for reverse cementing.

5.1.3 Floating equipment

In Phase 1 it was determined that floating equipment or other methods to control fluid fill-up and flow back once the RCPC placement has been completed will be needed. There have been a significant number of patents specifically for reverse cementing floating equipment ideas issued over the last few years. Generally the ideas are based on stopping inflow into the ID of the casing after the cement has reached the float shoe/collar. A potential issue identified was that the use of any restriction at the bottom of the casing could cause the ECD to increase. This increase may make using floating equipment at the bottom of the casing not acceptable for RCPC. Another option for placement of floating equipment is near the top of the casing.

Functional requirements determined in Phase 2 for RCPC float equipment are:

- The floating equipment must have the minimum ECD possible, e.g. as large a flow path as possible

- The floating equipment must remain open while the cement is placed. If it closes prematurely then the reverse cement job could squeeze off leaving cement in the work string, which would be difficult to dump or reverse out while still attached to the liner, before the liner hanger is set.

- Floating equipment must not limit the options of what can be run on the bottom of the liner casing for reaming in the hole – particularly while reaming in while circulating in the reverse mode.

- An inter string run inside the liner casing can be used to keep the floating equipment open and take returns back to the top of the liner during reverse cementing. Once the liner hanger is set the inter string can be moved up and let the float valve(s) close. Excess cement pumped into the ID of the inter string can be dumped on top of the float equipment by pumping in the conventional manner, or it can be reversed out by pumping down the riser.

(Note: The friction of pumping up the inner string needs to be taken into account when considering ECDs.)

- The floating equipment can be run near the top of the liner and held open by a stinger (inner string).
- If the floating equipment is needed to aid in flow into the casing ID, then the floating equipment should be run near the bottom of the casing. (Note: Floating equipment is not a primary well control valve, it is not designed to seal gas and it has a limited capability to hold differential pressure from below.)

All floating equipment run on reverse cementing applications should probably seal in both directions once it's closed, e.g. opposed flapper valve floating equipment – This prevents the circulation of fluids inside the ID of the liner or above the top of the liner, e.g. dumping or reversing out excessive cement from a inter string from adversely affecting the newly placed cement.

From an operator's perspective the selection and placement of floating equipment for reverse cementing will be done on a well by well basis. The two key considerations are to minimize ECD's during cementing and help control the flow into the ID of the casing while running in the hole.

5.1.4 Other Considerations

A full open reamer shoe could be used on the end of the casing to allow reaming into the hole. These can be purchased as a saw tooth shoe, Texas pattern, tiger tooth pattern, etc. These shoes allow the operator to get ledges and oval sections of the hole more easily than simple circulation and push through the restrictions.

Figure 6: Full Open Reamer Shoe example

5.1.5 Tool operations mechanisms

Phase I results have shown that a challenge of deepwater RCPC will be to accurately identify when cement reaches the casing shoe to avoid incomplete cementation around the shoe or a large amount of cement to drill out from the casing. When cement has filled the shoe track area, pumping can be stopped. If more cement than necessary is pumped the cement left in the casing will need to be drilled out, which increases cost and rig time. However, stopping before the cement has reached the shoe can result in incomplete cementation around the shoe, would result in reduced zonal isolation at the shoe and increased cost to the rig through remedial costs. Previously on some land-based RCPC jobs radioactive tracers were used, however this is considered undesirable offshore so other methods of fluid identification will need to be investigated and tested. Various methods could be used to detect the location of fluids downhole or trigger the operation of downhole crossover tools or valves. These methods include balls, darts, RFID tags, chemical tags, mud pressure pulse, wire drill pipe, hydraulic control lines from the surface, mechanical or gas powered springs, or any combination of these.

RFID Applications Downhole: RFID technology helps to replace or complement current downhole applications. RFID technology helps to improve communication with downhole tools and can be used for a wide variety of operations which include opening and closing valves. For downhole purposes, RFID components consist of a tag and a reader. The tag is dropped from the surface into the pipe while the reader is attached to the tool going downhole. The tag is programmed with a command through the use of software in a computer. The reader is usually accompanied by an antenna, battery pack, and a motor.

The challenges that need to be overcome while using RFID include the size of the tags, number of tags required, battery life, and operating conditions that the RFID system can endure. The Tags have reduced in size since the first application in the North Sea from about 1 to 0.35 inches in length.[3] The significance of the tag length is that if the tags are too long, they may interfere with systems in the downhole assembly such as MWD tools.

Ultimately, RFID application is only favorable if the Tag/Reader system can function under normal downhole operating conditions. P.M Sinder and Tom Doig showed the use of RFID in closing and opening a downhole circulating sub at 10,100 feet.[3] During circulation, multiple tags were dropped with commands instructing the reader to open the sub. Once the first tag passed the reader downhole, pump pressure was greatly reduced indicating communication between the tag and reader. Multiple tags were dropped to ensure that there was no case of tags getting

[3] Phillip and Doig, SPE-113842-MS

stuck to drill pipe and not reaching the reader. The reader was programmed to only decipher commands from one tag thereby rendering the other tags redundant once the command was received. This eliminated the possibility of multiple commands being sent to the reader. Testing conducted at 302°F on the batteries indicated a max operating time of twenty (20) days. Also, velocities in excess of 10m/s were achievable for tag detection for the antenna.

Iain Adan, presented a case study of a successful RFID enabled completion in the Middle East.[4] It studied the use of a single RFID module to control a completion system that includes a packer, circulation sleeve and downhole barrier valve. RFID was used to close and open a barrier valve for tubing testing, to set production packer and open/close sliding sleeve for annulus circulation. The system was run at 275°F and 5,000 psi. Mads Grinrod et al. studied the application of RFID for drill pipe, downhole applications, and the temperatures and shock/vibrations needed to be overcome.[5] RFID tags have been shown to have good performance in drilling fluids, pipe dope, and water. In order to show that RFID technology can withstand downhole conditions, several tests have been conducted including temperature cycles between 86°F and 410°F and pressures up to 10,000 psi. Shock, vibration and direct impact tests were also conducted.

Passive radio identification devices can be used as means of detecting drill pipe depth downhole. In the United States patent application, Joseph Zierolf described an innovative approach for determining casing and drill pipe position with the aid of radio identification devices combined with a downhole tool that has an inbuilt transmitter and receiver.[6] Precise depth measurements are vital in the drilling and completions industry since activities such as cementing/fluid placement volumes are largely based on well depth. Inaccurate depth data leads to inaccurate volumes and subsequently bad cement jobs. The modulus operandi involves the placement of several passive radio identification devices on each casing or drill pipe joint. In order to determine casing or drill pipe depth, the downhole tool, which has a radio frequency transmitter and receiver attached, is lowered down hole and sends a constant signal. Upon receiving this signal, the passive radio identification device resonates and transmits a response. The response is received by the downhole tool and sent to a surface computer. The downhole tool can also be modified with a battery so that all the information can be stored downhole and deciphered when the tool is retrieved from the well.

The need to properly identify the interface between drilling and completion fluids during a cementing operation cannot be overemphasized. In conventional cementing operations,

[4] Iain Adan, SPE. SPE-166182-MS
[5] Grinrod, et al. SPE-163449-MS
[6] US 6,759,968 B2

inaccurate depiction of these interfaces could lead to drilling mud contaminating the cement in the annulus. Reverse circulating aims to reduce this problem by pumping through the annulus rather than through the drill pipe. As a result, there is a need to properly identify the cement/mud or cement/spacer interface to determine when the cement reaches the casing shoe. Robert Dillenbeck and Bradley Carlson, in a patent application described an apparatus for detecting the cement/mud or cement/spacer interface[7]. The apparatus consists of a sensor that is attached to the lower part of the casing shoe, and a detectable device that emits radio frequency identification signals (RFID). The detectable device or transponder emits signals that are detected by the sensor attached to the base of the casing shoe. Once the signal is detected, more fluid is prevented from being pumped through the activation of a valve and the subsequent pressure increase noted by the operator at the surface.

RFID technology has been shown to withstand downhole conditions and the technology is generally expected to be successful in the industry. The downhole conditions/obstacles include tag size, vibrations downhole, loss of communication, and reliability. The technology has been successfully used to open/close valves and set packers. As a result, application in well completions/cementing is expected to be positive. Potential applications of RFID technology to deepwater RCPC is its use in the detection of cement location downhole or the activation of downhole tools. Limitations for RFID applications to deepwater RCPC are that if the receiver is located on the casing in the open hole section, there is a possibility for tags to get lost or stuck in the formation before reaching the receiver.

Chemical Tags: Currently, there is limited literature on practical applications of downhole tools controlled via chemical changes such as pH. The more common methods of tool activation widely available with field tests include tools activated via specific flow and pressure changes. While electronic pH meters are available, their actual application in a down hole trigger system is not well documented even for drilling fluids and as such is even more remote for cement. Available literature focuses on actual pH measurement using pH meters and pH sensitive dyes that provide in-situ measurements. For example, a pH downhole sensor has been used for in-situ pH measurement of formation water at reservoir conditions.[8] It involved using pH-sensitive dyes which tend to change color depending on the pH of the accompanying fluid.

A preliminary laboratory investigation into possible chemical triggers or markers for downhole tools was conducted. The objective was to evaluate a chemical system that acts as a chemical trigger for potential application in deepwater RCPC. Assumptions are that the method of activation would be a sequential change in pH from pumping a low pH chemical tracer. The

[7] US 6802373 B2

[8] Raghuraman, et al. SPE-93057-MS

detection point for the strongest signal is located inside the work string before the crossover point. Other potential placement for the detector would be inside the casing shoe or as part of the crossover tool for detection of cement location or for activation of floats or the crossover tool. A detector placed lower in the well may not be reliable on its own since the risk of fluid contamination and intermixing increases in the open hole annulus, causing an unclear pH signal. A differential pH of 5 was targeted, and the trigger process would be activated by the detection of two changes in pH. The primary fluid being pumped (spacer or mud) would be assumed to have a relatively high pH. This fluid would be followed by a low pH chemical tracer, then another high pH fluid. This drop in pH and subsequential increase is intended to reduce a 'false positive' effect. This scenario for a chemical trigger is shown in Figure 7.

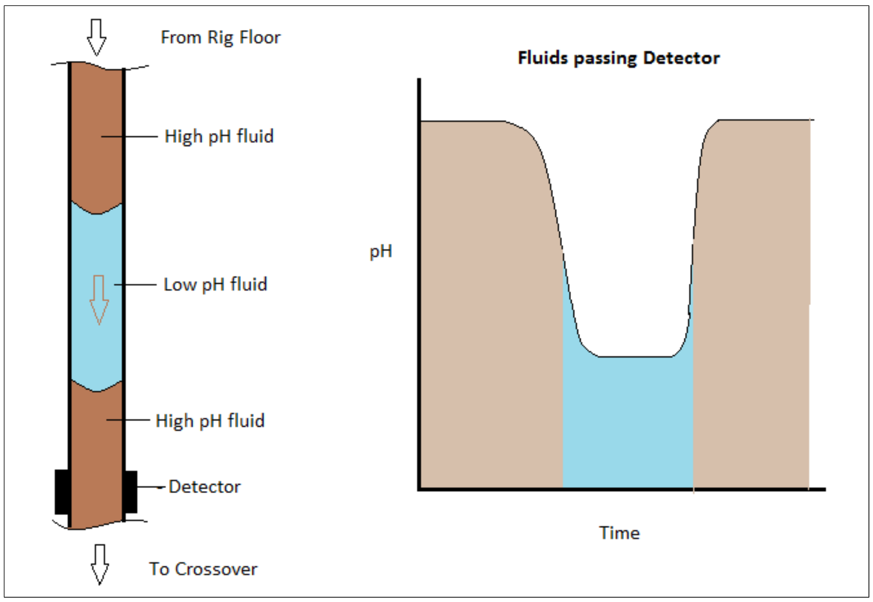


Figure 7: Example of a pH Chemical Trigger Operation

A combination of generic cementing spacers and chemical tag fluid has been evaluated. The chemical tag fluid designed for this study was made up of ~99% water, 0.1% citric acid, and 1% surfactant. The pH of the spacers ranges between 8 and 9 while the pH of the chemical wash designed is 2.8. For design purposes, it was assumed that the chemical tag will be pumped in between the spacers. As with any fluid pumped downhole during cementing jobs, the cementing tag fluid was evaluated for rheological compatibility. Wettability was also evaluated since the design assumption was that this chemical tag would be pumped with the spacer and a dual function to also assist with mud removal and hole cleaning would bring added benefit. Tests descriptions and results for the chemical tag fluid and spacers can be found in Appendix E

Others: Other potential methods of tool operations include hydraulic lines from surface attached to the pipe, balls launched from the surface, electric wire line or fiber-optic lines, or mud pressure pulse. One example is the activation of an annular casing packer that is remotely activated using a wiper plug. For shallow applications, the packer is set using an acoustic wave generator on the rig floor. The signal is sent downhole via the casing string to a receiving sensor in the packer's electronic module. This signal is decoded and the setting sequence is initiated. For deep well applications, sensors are located downhole that sense the magnetic field produced by the wiper plug. Once the magnetic field is detected by the sensors, the setting position of the packer is initiated. The electronic module of both systems are powered by battery packs with operating temperatures ranging from 100 - 392^{o}F and run times of 336 hours.[9]

Future development of deepwater RCPC mechanical controls requires implementation of a way to reliably detect cement location downhole during placement, particularly in the casing shoe track to confirm job completion. Technology investigated by RPSEA project # 10121-4504-01 on Intelligent Casing-Intelligent Formation Telemetry (ICIFT) could have applications to address this particular challenge of RCPC. Stalford et al, describe the implementation of intelligent casing sensors to combat the age old problem of downhole information gathering.[10] Obtaining real time downhole information during or before completion operations is vital. To accurately obtain distributed downhole data in producing wells, an intervention is usually required. The need to eliminate the time, money, and effort required for well interventions justifies the design of an intelligent casing sensor capable of sending downhole data. The sensors can be placed in cement, the formation, and on the casing. The system can be equipped with fiber optic distributed sensing in conjunction with radio frequency intelligent devices to enhance data transmission. The system is beneficial as it reduces the need for well intervention, is not affected by weather conditions, and ensures constant well monitoring. On the other hand, the need for specific steel grades of casing for sensor attachment, hole attachments in the casing, and unreliable wireless communications may hinder this technology. Real-time monitoring capabilities could allow for the positive identification of cement position downhole in the annulus during RCPC. Also, pressure and temperature sensing capabilities would allow for validation of RCPC placement simulations, and data for refinement if needed.

Also, RPSEA project # 10121-4501-01 may also provide a future avenue for cement detection downhole. This project focused on the creation of a smart cement system with better sensing capabilities to aid wellbore monitoring and small-scale laboratory tests to evaluate performance.[11] The electrical resistivity of the cement is measured to determine the level of contamination with oil based mud (OBM), and in small-scale experiments, resistivity was used

[9] Pleasants et al., SPE 160217
[10] Stalford et al., OTC 25161-MS
[11] Vipulanandan and Heidari, OTC-25200-MS

to determine the positions of various fluids in a modeled annulus. This type of instrumentation and methodology capable of differentiating OBM and cement downhole has clear applicability to RCPC. While this method of using resistivity measurements to differentiate fluids has been validated in the laboratory, scaling this technology to the field is a challenge.

5.2 Modeling and Numerical Simulations

Commercially available software packages are unable to model the flow-path of a deepwater reverse-circulation cementing process due to the complex well architecture and changes in downhole flow path. The COMSOL Multiphysics finite-element software package was used to develop a robust model capable of handling the deepwater reverse-circulation cementing process. In Phase I this COMSOL model had been successfully applied to a small-scale well to predict temperatures and pressures along the well. Further development and expansion of the FEA modeling capabilities were extended in Phase 2. Evaluations using commercial simulators currently available to the industry and the development of workarounds within the software were conducted.

5.2.1 Commercial Simulators

Landmark's WellCat® temperature simulator was used to study and model the temperatures throughout the wellbore for RCPC in deepwater wells, and the *Opticem®* placement simulator was used to evaluate deepwater liner and casing strings. Traditional RCPC applications, such as land-based jobs where fluids can be injected directly into the annulus from the surface for placement can be modeled by commercially available software such as *Opticem®* and *Wellcat®.* The limitation of the *Wellcat®* software used is that a deepwater reverse-circulation cementing configuration cannot be applied; the underlying assumption in a reverse circulation simulation is that fluids are injected into the annulus from the surface in all cases of RCPC and this flow path cannot be modified. While this configuration is suitable for land and shallow offshore RCPC setups, this flow path is unrealistic for deepwater operations where a riser and sub-sea wellhead is used; for HS&E and operational reasons, cement will not be pumped directly down a riser. An illustration of this limitation is shown in Figure 8. For deepwater RCPC, the expected flow path of fluids is down the drillpipe, through a crossover tool below the BOP, then into the annulus so that cement is injected into the annulus below mud line. This complex flow path cannot be modeled directly by current commercial software. However, a workaround reverse circulation operation where fluids are injected into the well through the annulus can be run. This workaround includes running the temperature simulation in 'production' mode vs. 'drilling' mode, and defining the casing as production tubing. Once these modifications have been made, a reverse-circulation temperature simulation can be run.

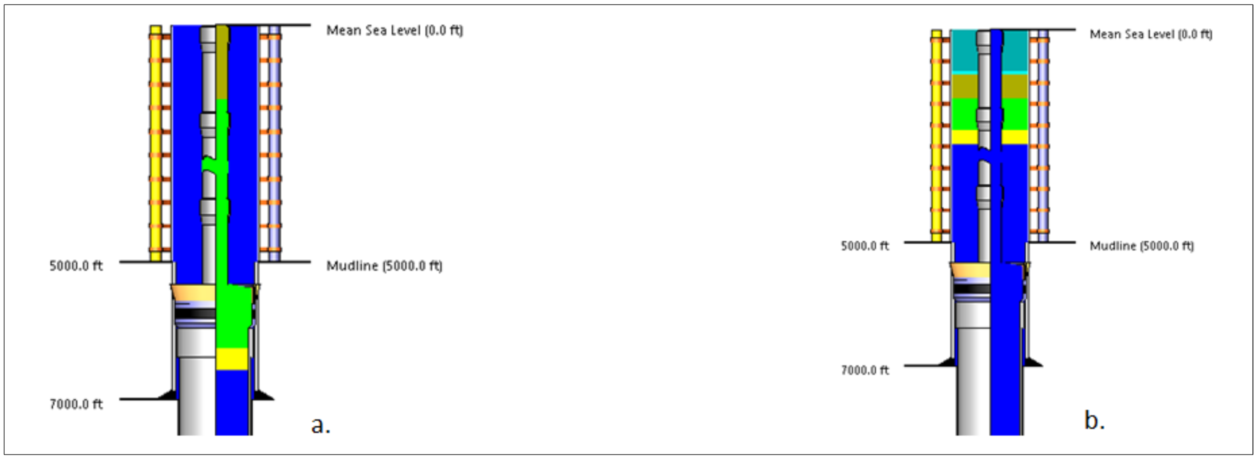


Figure 8: (a.) Conventional Placement Simulation (b.) Reverse Placement Simulation with commercial software

In an effort to obtain as reasonable comparison as possible between simulations using conventional and deepwater RCPC techniques, the baseline conventional simulations from Phase I were re-ran and their results differ slightly from those presented in the Phase I interim report. For this portion of the project, all simulations were run using the same software package to minimize discrepancies. The same fluid properties were used for both conventional and deepwater RCPC simulation.

Conventional Simulation

Primary cementing simulations were performed for multiple strings on multiple hypothetical wells. Design considerations included cement fill volumes and dynamic well security. The conventional simulations output fluid temperatures for the interfaces ("first sack, last sack" temperature profile), equivalent circulating density, and fluid pressures.

Deepwater RCPC

As was stated in the Phase I interim report, currently available cementing simulations cannot directly model the flow path geometry of deepwater RCPC. All are capable of performing conventional cementing simulations and some are capable of doing reverse cementing simulations, but one is limited in choosing one or the other. For deepwater RCPC, it is necessary to be able to flow in both configurations (conventional above a crossover, and reverse below) for the same job. A method was developed to be able to use commercial cementing simulation software to perform deepwater RCPC simulations. The generalized procedure is described below. An example procedure for using Landmark's WELLCAT® software is given in Appendix A

Above the Crossover: Configure a cementing simulation as for a conventional job (tubing-side downward flow). This simulation is meant to model the cementing operations above the crossover point.

- Define all well parameters as for a conventional cementing job. Define pumping operations as for a reverse cementing job as seen from surface, but performed as a conventional job.
- Operations should be defined such that the simulator produces results for the fluid fronts at key depths (e.g. spacer at the mudline or cement at the crossover point). This may lead to operations with the same fluid and rate being split into smaller volume steps for later convenience.
- Rates and pressures for using a reverse cementing job in a conventional configuration may lead to the simulation to show losses (fracturing) or influx (blowout) in the open-hole section. Simulator "safeties" should be disabled, bypassed, or ignored for the region below the crossover. Burst and collapse pressures above the crossover should still be considered.

Outputs from the "conventional" simulation should include the fluid temperature and pressure as each fluid reaches the mudline and the crossover. Additional points of interest can be analyzed if desired. The fluid temperature and pressure at the crossover will be used as inputs for the "reverse" simulation.

Below the Crossover: Configure a cementing simulation for a reverse job (annulus-side downward flow). This simulation is meant to model the cementing operation below the crossover point.

- Define the surface of the well as the depth of the crossover. Pore pressure, fracture gradient, geothermal temperature, "surface" temperature (geothermal temperature at the crossover), and other well parameters will need to be translated to the new depth reference.
- Define the pumping operations for reverse cementing. Use the same fluids, volumes, and rates as for the conventional simulation. The simulation should include original fluid displaced from the drill pipe above the crossover after any pre-job mud circulation. The reverse operations should mirror the conventional operations as seen from the crossover point.
- Again, operations may be split into smaller volumes for convenience. An example table with pumping operations is shown below; the parenthetical comments for the "conventional" simulation refer to fluid front locations at the end of the operation.

Table 1: Example operations

"Conventional" Simulation (Above Crossover)	Reverse Simulation (Below Crossover)	Volume [bbl]	Rate [bbl/min]
Pre-job Circulation	Pre-job Circulation	9000.0	10.0
Spacer	Mud	100.0	10.0
Cement (Spacer @ Mudline)	Mud	72.8	8.0
Cement (Cement @ Mudline)	Mud	100.0	8.0
Cement (Spacer @ Crossover)	Mud	122.5	8.0
Cement (Cement @ Crossover)	Spacer	100.0	8.0
Cement (Remainder)	Cement	374.0	8.0
Displacement (Displacement @ Mudline)	Cement	172.8	10.0
Displacement (Displacement @ Crossover)	Cement	222.5	10.0
Displacement	Displacement	17.7	10.0
Displacement	Displacement	100.0	5.0

The fluid temperatures at the crossover from the "conventional" simulation are used as the injection temperatures for the reverse simulation. Tubing-side fluid pressures can similarly be used for injection pressure. Annular-side fluid pressures just above the crossover should be input as back pressure. Alternatively, hydrostatic pressure in the annulus above the crossover can be used as an approximation if friction pressure is not significant. If required, additional operations for shut-ins simulating wait-on-cement can be added. Outputs from the reverse simulation should include fluid temperature and pressure profiles in the annulus.

Interpretation: Using the results from both simulations, a data table can be constructed. An example is given below in Table 2:

Table 2: Example Temperature and Pressure Data for Deepwater RCPC Workaround

Description	First Sack Time [min.]	First Sack Temperature [°F]	First Sack Pressure [psi]	Last Sack Time [min.]	Last Sack Temperature [°F]	Last Sack Pressure [psi]
Injection	10.00	80.00	1601.03	106.17	80.00	1642.84
@ Mud Line	31.60	75.32	5851.62	123.45	77.47	6164.07
@ Crossover	59.42	117.17	13392.15	145.71	112.29	12104.12
@ End of Job	167.47	150.06	15212.90	167.47	127.59	10498.67
WOC (1 of 6)	407.47	158.14	16992.37	407.47	135.48	12236.35
WOC (2 of 6)	647.47	161.87	16989.95	647.47	136.95	12235.70
WOC (3 of 6)	887.47	164.66	16988.65	887.47	137.56	12235.50
WOC (4 of 6)	1127.47	166.94	16987.76	1127.47	137.91	12235.42
WOC (5 of 6)	1367.47	168.89	16987.07	1367.47	138.14	12235.39
WOC (6 of 6)	1607.47	170.59	16986.51	1607.47	138.30	12235.36

As defined above, the results at the end of each operation yielded data points with the fluid fronts at relevant locations. The “Injection”, “@ Mud Line”, and “@ Crossover” data points were taken from the “conventional” simulation for above the crossover. The “@ End of Job” and “WOC” data points were taken from the “reverse” simulation for below the crossover.

Similarly, a data table can be constructed using annular fluid pressures from the “reverse” simulation to analyze circulating pressures. In the example below (Table 3), only the pressures at the previous shoe and the casing shoe were analyzed. However, any depth of interest can be chosen.

Table 3: Example Data for Deepwater RCPC Workaround

"Conventional" Simulation (Above Crossover)	Reverse Simulation (Below Crossover)	Time [min.]	Fluid Pressure @ Previous Shoe [psi]	Fluid Pressure @ Shoe [psi]
Pre-job Circulation	Pre-job Circulation	0.00	13163	17508
Spacer	Mud	10.00	11108	15209
Cement (Spacer @ Mudline)	Mud	31.60	11092	15207
Cement (Cement @ Mudline)	Mud	59.42	11091	15206
Cement (Spacer @ Crossover)	Mud	167.47	11090	15205
Cement (Cement @ Crossover)	Spacer	407.47	11076	15203
Cement (Remainder)	Cement	647.47	10698	15198
Displacement (Displacement @ Mudline)	Cement	887.47	10483	15197
Displacement (Displacement @ Crossover)	Cement	1127.47	10187	15195
Displacement	Displacement	1367.47	10174	15195
Displacement	Displacement	1607.47	10127	15213

The pressures can be compared to the fracture and pore pressures at the specified depths to analyze dynamic well security (Figure 9).

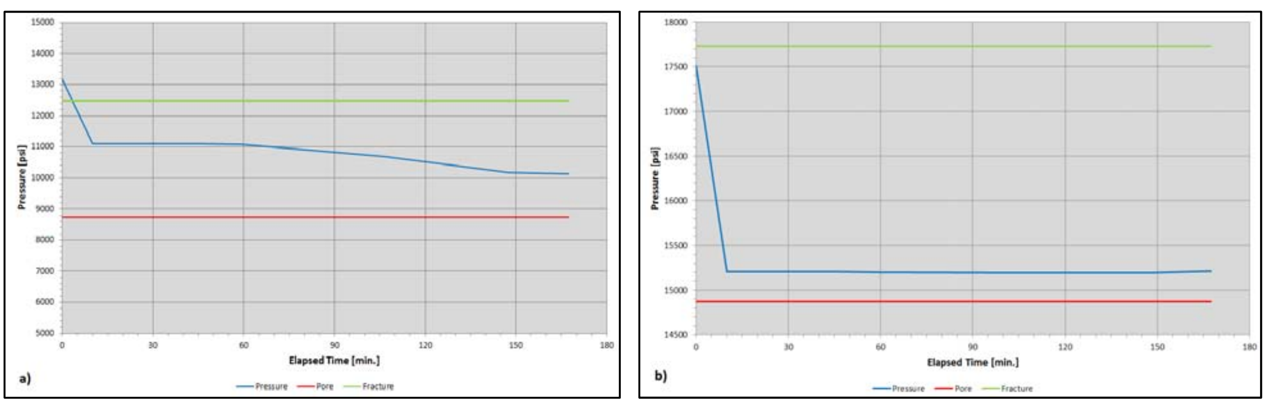


Figure 9: (a) Circulating Pressure at Previous Shoe (b) Circulating Pressures at Casing Shoe

Known Limitations: Most cementing simulators allow you to set the injection temperature for the fluids, but require that the injection temperature be constant for each pumping operation. In the case of large fluid volumes (e.g. pre-job circulation), this could lead to inaccurate temperature results. The resulting temperature and pressure profiles are somewhat simplistic.

Breaking the pumping operations into smaller steps increases the resolution, but also increases the time to perform the simulation.

5.2.2 Finite Element Modeling for Deepwater RCPC

The COMSOL Multiphysics software package was selected for the custom FEA model because it is a robust, generic finite-element software package that has sophisticated modules for solving non-isothermal fluid flows in complex geometries. The equations which govern the pressure and temperature are partial differential equations. A finite element analysis (FEA) is therefore an appropriate and powerful method. This software has built-in modules for heat and momentum transfer, although the form of the equations had to be modified for this application.

Bittleston published the first two-dimensional temperature simulator (1990).[12] He began with an analysis of one-dimensional simulators and concluded that they are unable to capture the complicated heat transfer during cementing and provided a convenient simplifications and non-dimensionalization of the governing equations. He solved this equation with a finite difference method, but any method can be used. For laminar flow, he assumes that a velocity profile is known in advance. With minor modifications, his method is used to model the temperature.

The pressure modeling involves calculating the hydrostatic pressure and the frictional pressure drop across each region. The static pressure is trivial, so the problem is reduced to the classic problem of calculating frictional pressure drops across pipes and annuli from a specified flow rate. This is complicated by the non-Newtonian rheology of drilling fluids. However, a large number of methods, both analytical and numerical, for calculating these pressure drops have been developed. Analytical methods are well-known and can be found in many textbooks.[13, 14] (For more complicated situations, like flow with large temperature variations or flow through eccentric annuli, numerical methods must be utilized. This poses a challenge because most numerical methods like Finite Element Analysis (FEA) require continuous functions, and yield-pseudoplastic fluids exhibit a discontinuity at the yield stress. Papanastasiou developed an alternative formulation of the Bingham constitutive equation which approximates the “true” Bingham behavior, while ensuring continuity[15]. This method is directly applicable in FEA methods and allows pressure drops to be calculated in any arbitrary cross-sectional shape by solving the Navier-Stokes equations with the proper expression for the effective viscosity.

The following assumptions were made for this model:

[12] S. H. Bittleston, SPE-20448-MS
[13] Chabra and Richardson, 2008
[14] Nelson and Guillot, 2006
[15] Papanastasiou, 1987

- The wells of interest are perfectly vertical, with no eccentric annuli.
- In regions without flow, such as the casing wall and the surrounding formation, convective heat is neglected.
- The governing equation for pressure and velocity is the Navier-Stokes equation.
- The velocity during cementing wells is assumed to be unidirectional in the vertical direction.
- The Navier-Stokes equation and the equation of continuity assume fluids with constant density.
- Multi-phase flow modeling is flow-rate constrained, rather than pressure constrained.
- Fluid-fluid interfaces are perfectly sharp and moves with the average velocity of the fluids
- The existence of an interface has a negligible effect on the rest of the flow.

In COMSOL, the simulation was set up as a multi-phase flow problem to solve for temperature and pressures simultaneously. Flow rates were specified in the simulation, which allowed for multiple velocity fields to be calculated then combined based on the location of each fluid interface. This iterative approach is shown in

Figure 10. Other calculations produced by the model include pump pressure, U-tubing effects and required back pressure to prevent U-tubing.

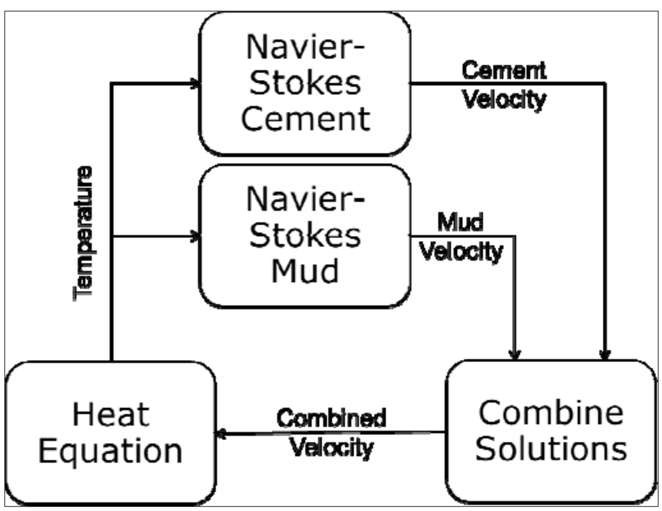


Figure 10: Coupling of Equations for Multiple Fluids

A more detailed discussion of the governing equations, the rescaling methods, boundary conditions and other modeling parameters can be found in Appendix B

5.2.3 COMSOL Validation

To validate outputs of the COMSOL model, the model was altered to run a conventional primary cement simulation and the results were compared to a simulation made with commercial software. The same fluids, rheology, formation temperatures and pump rates were used for both simulations. Bottom-hole circulating temperature (BHCT) and the first-sack/last-sack temperatures were compared and are shown in Figure 11 (a) and (b). Commercial simulator results show only the first-sack/last-sack temperature and the COMSOL output shows the temperatures throughout the cement depth. Temperatures shown are at the end of placement.

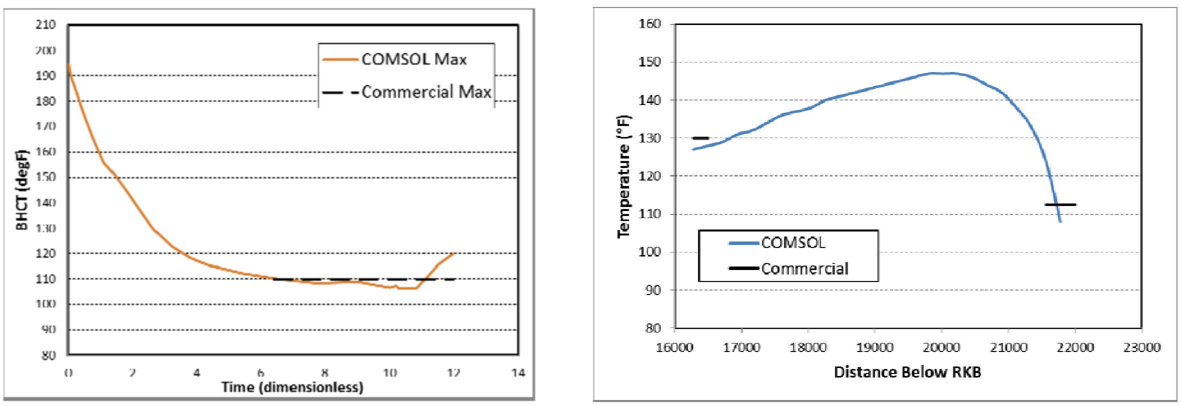


Figure 11: (a) Comparison of BHCT between commercial and COMSOL (b) comparison of first/last sack temperatures

5.2.4 COMSOL Modeling Results for Temperature

The simulator was used to analyze both conventional and reverse placement in three casing strings in two different wells, with three different casings in each. As far as possible, job parameters, such as flow rates, were maintained between reverse and conventional placement. An example of the scaled geometry and each well region represented in the COMSOL analysis are shown in Figure 12. A cross-section of the well that includes the riser, drill pipe down to the crossover point, casing/liner and the previous casings exposed to flow. Casing and riser wall and formation properties are also taken into consideration.

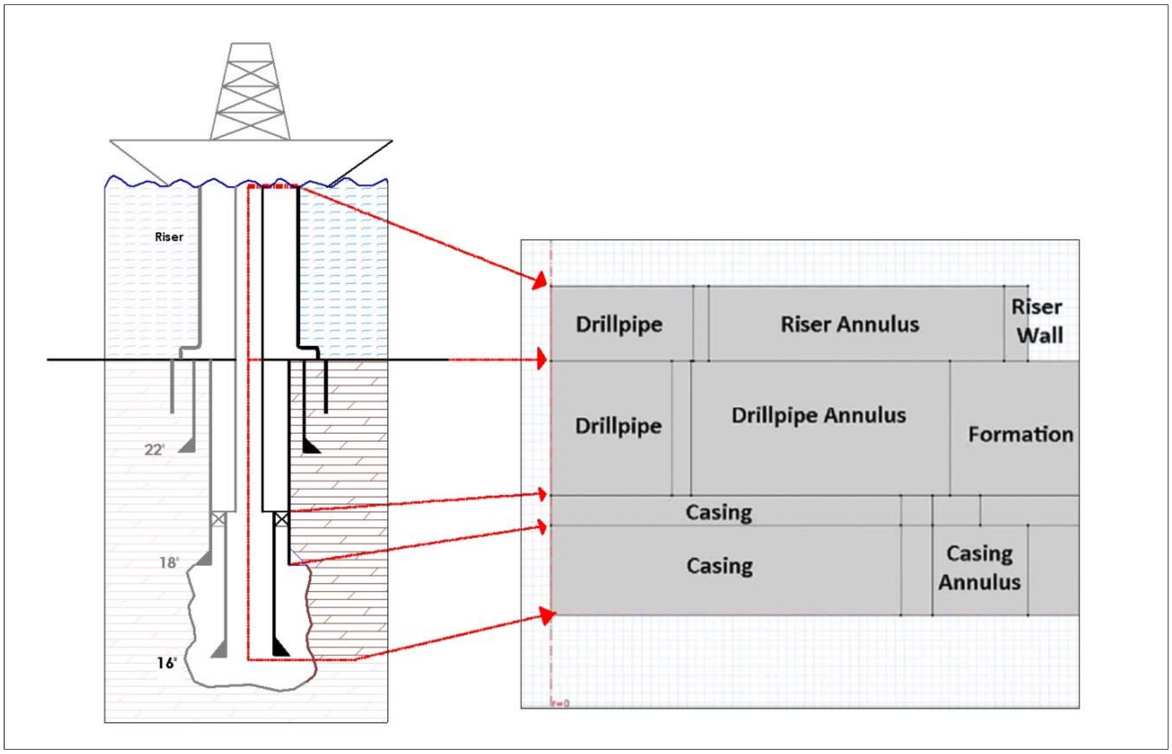


Figure 12: Well geometry representation in COMSOL

Temperature surface plots for reverse and conventional circulation for the Figure 12 well geometry are shown in Figure 13. The arrows in the plots indicate the flow path.

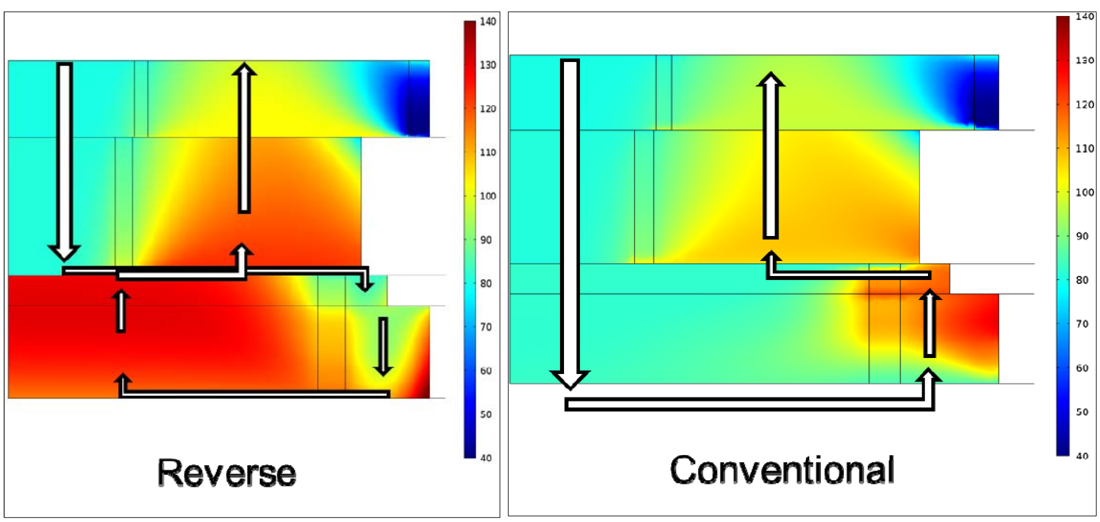
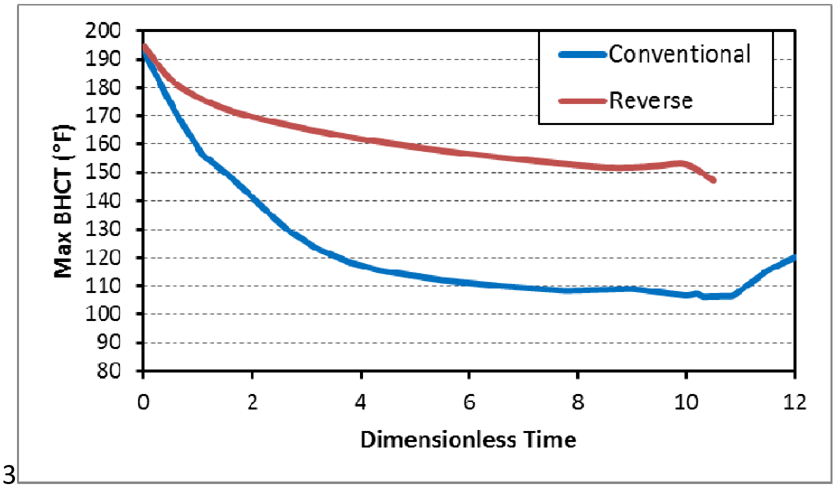


Figure 13: Temperature surface plots after mud circulation for conventional and reverse circulation

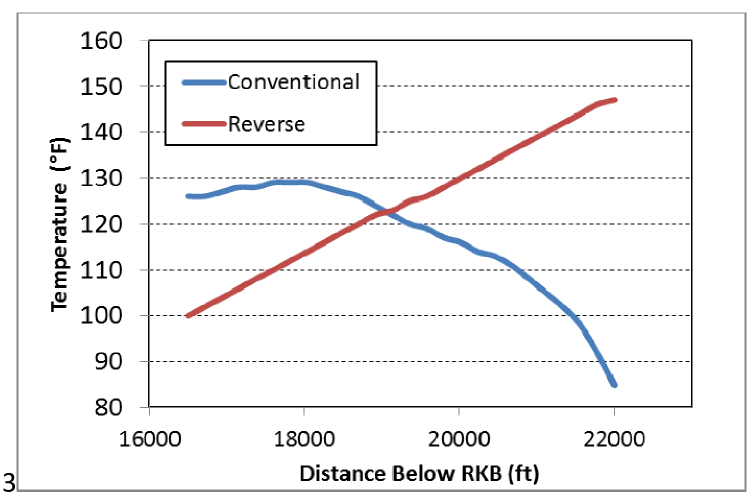
Overall, reverse circulation produces higher bottom hole temperatures since most of the heat transfer in the well is occurring in the annulus, where the fluid is in direct contact with the formation. The central regions of the drillpipe and the casing are effectively insulated by the fluid in the annulus. In conventional circulation, less heat is transferred to the fluid on the way down than it does in reverse circulation, producing a lower BHCT. A comparison of the conventional and reverse BHCT over time is shown in Figure 14.



3

Figure 14: Bottom-Hole Circulating Temperature (BHCT) in conventional and reverse circulation

A comparison of the cement temperature in the annulus at the end of placement is shown in Figure 15. In reverse circulation the cement enters at the top of the annulus, and then heats up as it travels down to the hotter regions of the well. Because the flow is in the same direction as the geothermal temperature gradient, the temperature increase is fairly linear. In conventional circulation, the fluid enters the annulus at the bottom of the well and increases in temperature as it travels up the annulus. As the cement reaches the cooler regions towards the top of the annulus, it no longer draws heat from the formation, and eventually begins to lose heat to the formation and decreases in temperature.



3

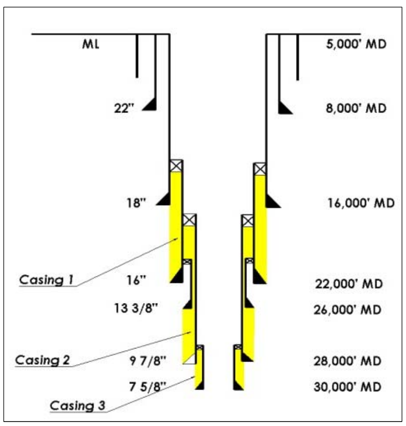
Figure 15: Temperature in the cement at the end of placement

A more detailed description of this analysis can be found in Appendix C

5.2.5 COMSOL Modeling Results for Pressure

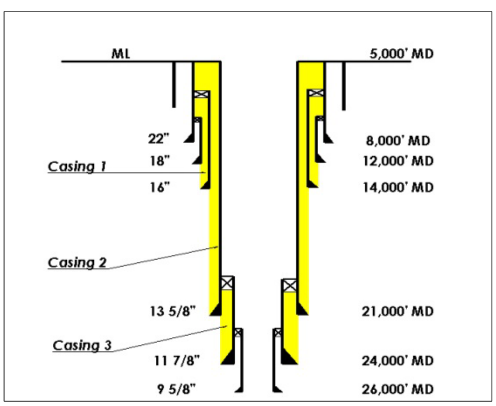
To evaluate if RCPC is an improvement over conventional cementing the ECDs at the bottom-hole and at the previous shoe will be compared for both conventional and reverse placement. Maximum ECD results during cement placement in example wells 1 and 2 are shown in Table 4 and Table 5. Zones of interest in each well are highlighted in yellow. For the casing sections in well 1, ECDs for RCPC are reduced at bottom hole, but increased at the previous shoe. In well 2, ECDs are reduced at both bottom hole and at the previous shoe by RCPC placement. The ECDs in conventional placement for well 2 are extremely high, because of extremely tight liner gap.

Table 4: Maximum ECDs in well 1



		Conventional	Reverse
Casing 1	Bottom Hole	14.5	12.6
	Prev. Shoe	12.7	13.5
Casing 2	Bottom Hole	14.6	14.2
	Prev. Shoe	13.4	14.6
Casing 3	Bottom Hole	14.3	13.2
	Prev. Shoe	12.8	14.4

Table 5: Maximum ECDs in well 2



		Conventional	Reverse
Casing 1	Bottom Hole	38.2	16.1
	Prev. Shoe	41.8	16.6
Casing 2	Bottom Hole	26.1	15.8
	Prev. Shoe	30.2	17.1
Casing 3	Bottom Hole	18.1	14.0
	Prev. Shoe	18.1	14.3

ECD increase at the previous shoe is an important phenomena, and the reasons why involve a more thorough hydraulic analysis, which is summarized in Section 5.2.6. From these comparative simulations, deepwater RCPC is most effective in wells with tight liner gaps, reduces ECDs at bottom-hole. Additional details of pressure results can be found in Appendix A The pump pressure, lift pressure, and back pressure for one conventional job are shown in Figure 16 (a). The longest portion of the job is the mud conditioning phase, where drilling mud is circulated. Because there is one fluid throughout the well, the lift pressure is zero, and the pump pressure is relatively constant. Once cement is being pumped, the lift pressure becomes negative and drives the pump pressure below zero, indicating U-Tubing if back pressure is not applied. Once the cement reaches bottom-hole, the lift pressure increases dramatically, which drives the pump pressure up.

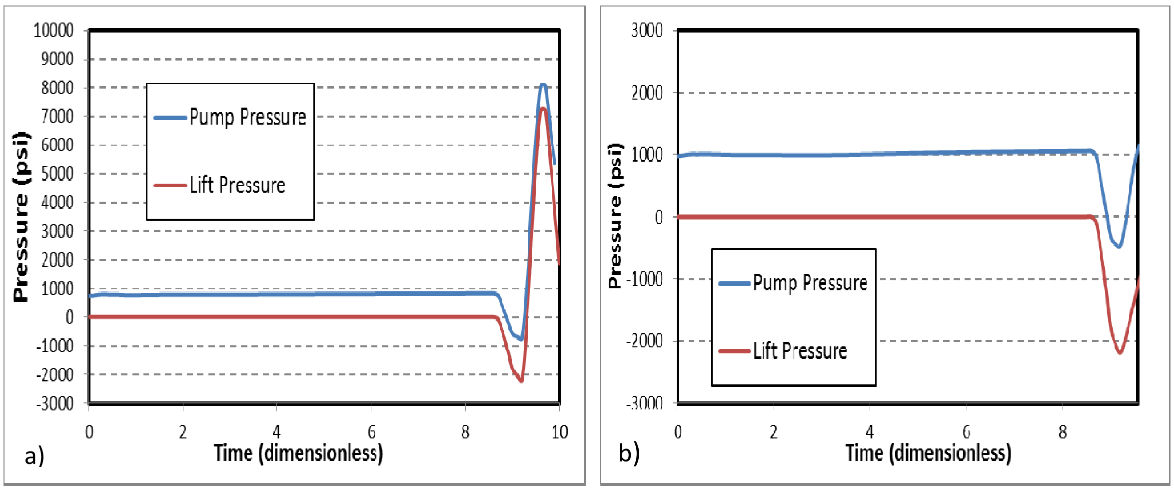


Figure 16: Pump, lift and back pressure(well 1, region 2) (a) Conventional placement (b) reverse placement

The analogous graph for reverse placement is shown in Figure 16 (b). The shape of the pressure curves is almost identical during mud circulation and the first part of cement placement. The same U-Tubing effect is seen shortly after cement placement begins. But because reverse placement does not require pumping the heavy cement against gravity, the lift pressure is always negative, which keeps the pump pressure much lower.

5.2.6 Hydraulic Analysis

If the ECD is reduced at bottom-hole and increased at the previous shoe, then there is a point between those two where the pressures in conventional and reverse circulation are equal. This point is known as the critical depth or the critical zone.[16,17] When designing a well for reverse circulation it is important to ensure that the weakest part of the formation is below this critical depth in order for RCPC to be effective. A more detailed discussion can be found in Appendix A

[16] E. Kuru, S. Seatter, 2005
[17] R. Moore et al., 2005

5.3 Cementing Materials

Cementing material considerations were studied to identify potential design and performance benefits and issues based on cement performance under deepwater conditions when placed by RCPC. Considerations included fluid intermixing, key aspects of spacer design, additive sensitivity, and wait-on-cement (WOC) time.

5.3.1 RCPC Slurry Design

Cement designs for RCPC are measured by the same test parameters as with conventional cementing, including thickening time, compressive strength development, gel strength development, free fluid, fluid loss and rheology. However, there are some design considerations and modifications that may be made to slurries for RCPC. Results and comparisons of conventional and reverse slurry designs can be found in Appendix E

In Phase 1, simulations were run for conventional placement using commercially available software. Cement slurries were then designed with commercially available oilfield additives based upon the simulation results. These conventional designs provided a baseline for comparison with slurries designed specifically for RCPC to aid in determining under which circumstances reverse circulation placement is advantageous over conventional placement. For intermediate casings, intermediate liners, and tieback strings, the desired API fluid loss was less than 100 mL and the desired free fluid was less than 0.2%. For production liners, the desired API fluid loss was less than 50 mL and the desired free fluid was zero. In all cases, the thickening times were based on pump time obtained from the ECD simulation plus a safety factor. These conventional designs were modified for the reverse-circulation temperature schedules developed in the modeling and simulation tasks. For these designs, it was assumed that BHP was equivalent to the conventional BHP.

In conventional placement, most of the slurry pumped is exposed to the bottom hole circulating temperature (BHCT) near the shoe. The slurry is pumped down the casing and up around into the annulus until the desired annular height is reached, and retarding additives are added so that the slurry remains pumpable during placement. The leading edge of slurry will have enough retarding additive to remain pumpable for the duration of placement plus a safety factor at BHCT or at the maximum circulating temperature in the annulus. As a result of this necessary retarder dosage and cooler formation temperatures higher up in the annulus, the top of cement (TOC) will be slower to set and gain compressive strength after placement.

Depending on string size and depth, placement by RCPC will often result in a different temperature profile from conventional placement due to the modified flow path. With reverse placement, slurry near the shoe and bottom of the annulus is exposed to the BHCT, while the slurry near the TOC is exposed to a lower temperature. Deeper strings with relatively smaller volumes of cement pumped will have less of a temperature difference between reverse and conventional placement. Slurries used in shallow to mid-depth well strings with large annular volumes or longer columns of cement are exposed to higher temperatures in general during reverse placement, as well as a larger formation temperature difference between the shoe and the TOC. These differences affects both required thickening time and WOC/compressive strength development. Based on literature review of past land-based RCPC jobs, adequate compressive strength development at cooler temperatures near the top of the annulus is a concern.

An example of a reverse temperature schedule compared to the conventional schedule is shown in Figure 17. These temperatures were used to design the slurries for the 16” liner in generic well #2, with the TOC 500’ below the previous casing in this example.

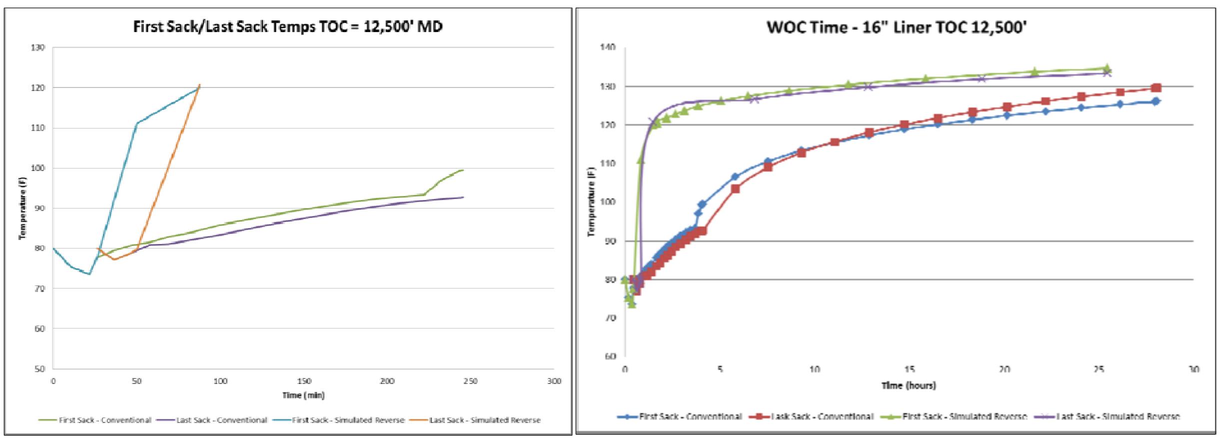


Figure 17: Conventional and reverse temperature schedules (Well Schematic #2, 16” liner)

In this example, RCPC placement has resulted in a higher maximum temperature (120^{o}F for reverse compared to 100^{o}F for conventional), a significantly shorter placement time (Approximately 2:45 h:min shorter for reverse placement), and comparable WOC temperatures for the top and bottom of the cement annulus. The placement times for these temperature simulations were based on fluid volumes and rates, and do not include tool operation times or safety factors. Due to the change in BHCT and placement time, a shorter thickening time is required for the reverse cement design (Figure 18).