CCEMC Project C110113

Permanent Sealing of Greenhouse Gas Emitting Wells

Final Outcomes Report

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Project Completion Date: **May 31, 2015**

Total CCEMC Funds Received:
CCEMC Funds Held Back:

Submission Date: **June 15, 2015**

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Executive Summary

CCEMC Project C110113,"Permanent Sealing of GHG Emitting Wells", assesses the use of certain bismuth-based metal alloys as a superior sealant for abandonment of oil and gas wells, for blocking natural gas leakage from the casing annulus of wells, and for permanent sealing of wells that penetrate geologic formations into which CO_2 is being injected for very long term sequestration purposes.

Bismuth is a metallic element with known properties that suggested its use described above:

- It expands volumetrically by about 4% when it solidifies from molten to solid state;
- It is non-toxic in contact with fresh water;
- When it is alloyed with other metals, the melting point of the resulting alloy is lowered to levels that are convenient for *in situ* melting and deployment in wells using conventional equipment and procedures.

The principal bismuth alloy studied in this project is a commercially available material that is 58 wt% bismuth and 42 wt% tin. This is a eutectic mixture that melts and solidifies at a temperature of 138^{o}C and expands about 1% by volume upon solidification from a molten state.

The studies that comprised this project were divided into three main milestones. The first was comprehensive measurement of corrosion of this alloy and steel well casing immersed in saltwater as a function of temperature, pressure, and pH from alkaline to acidic levels. Simply stated, the results of the corrosion investigation show that plugs in wells molded from this alloy should have a service life measured in thousands of years – a result especially important for sealing CO_2 sequestration wells.

The second milestone involved the design and construction of full scale physical models into which bismuth alloy was deployed using electrically heated purpose-designed tools under physical conditions similar to those encountered in most Alberta oil and gas wells. The resulting plugs were tested successfully to pressures exceeding Alberta regulatory requirements. Temperatures and other operating parameters were recorded and compared to computed values derived from unsteady state mathematical models that describe the physics of the process.

The third milestone was field testing the deployment of bismuth alloy plugs in eight wells with known gas leaks. The procedures that evolved from these tests are directly applicable to the repair of the very large number of leaking wells in Alberta and elsewhere and to the permanent sealing of CO_2 sequestration wells.

Project Description

1. Introduction and Background

More than 430,000 oil and gas wells have been drilled in Alberta. Natural gas leakage from a portion of these wells is not known with precision, but has been estimated at about 3.5 million tonnes per year CO_2 equivalent. One source of gas leakage occurs from operating and suspended wells through the cemented annulus between the production casing and wellbore wall and is referred to as surface casing vent flow or SCVF. Well operators are required to report such leaks to the Alberta Energy Regulator ("AER") and to repair them before the well is abandoned. One statistical study[9] estimated the proportion of Alberta wells that exhibit SCVF is about 14% as of 2005.

SCVF leakage is notoriously difficult and expensive to repair. Major Alberta operators report average repair costs of about $300,000 per well, and, according to industry anecdotes, particularly difficult examples have cost upwards of $8,000,000 to repair[9]. With costs of this magnitude, it is not surprising that companies tend to delay vigorously dealing with their inventory of such wells.

Another present and potentially major source of GHG leakage is abandoned wells without SCVF, but that have been plugged with the AER approved method of setting a mechanical bridge plug just above the production intervals and adding an 8 meter column of cement on top. Before January 1, 2008, the abandonment procedure after plugging was completed by cutting surface and production casing at least 1 meter below the surface and sealing the casings at that point with a welded cap. In 2007, a dangerous fire incident occurred when a backhoe struck and ruptured a buried well cap, releasing and igniting accumulated gas. AER's abandonment procedure defined in their Directive 020 was changed to subsequently require surface capping to be vented. Testing and international anecdotal evidence has shown that the bridge plug/cement combination is not a reliable method for sealing well casing against sustained gas pressure from below[19]. Bridge plug elastomer seals deteriorate with time and attack by acid gases, saltwater, and oxygen stripping corrosion inhibitors[10]. Universally used Class G well cement shrinks slightly during setting allowing gas to bypass a cement column[15]. In decades to come, a large number of wells abandoned in this manner are likely to begin to leak and require repair, and this could occur after well operators with statutory repair liability are no longer on the scene.

In view of the comments in the paragraph above and as regards well plugging for permanent abandonments, it is appropriate to note the requirements for sealants used in the North Sea and defined in the NORSOK Standard D-010, Rev 4, August 2012[13]:

"A permanent well barrier should have the following characteristics:

- **a) Provide long term integrity (eternal perspective)**
- **b) Impermeable**
- **c) Non shrinking**
- **d) Able to withstand mechanical loads/impact**
- **e) Resistant to chemicals/ substances (H2S, CO2 and hydrocarbons)**
- **f) Wetting to ensure bonding to steel**
- **g) Not harmful to the steel tubulars integrity**

Steel tubulars are not an acceptable permanent WBE unless supported by cement or a plugging material with similar functional properties as listed above (*internal and external*).

Elastomer sealing components in WBE's are not acceptable for permanent well barriers."

The "eternal perspective" for the long term service life of a sealant used for permanent well abandonments is defined in the NORSOK Standard as **greater than one million days**.

With GHG sequestration projects going forward wherein CO_2 is injected into geological formations, the concern with permanent sealing of wells becomes more acute. The fixing in the earth of injected CO_2 by natural chemical reaction to form solid carbonate rock proceeds very slowly[20]. Engineers designing CO_2 sequestration projects are seeking a minimum service life of 3000 years for plugs (see definition above for "eternal perspective") to seal injection, observation, and pre-existing wells that penetrate the target sequestration formation. No mechanical bridge plugs available on the market likely can meet this criterion[19].

It is in the context of the situations described above that Seal Well proposed the project reported upon here to develop new tools, materials, and procedures to solve the problems that are existing or emerging in future.

2. Technology Description

The purpose of the technology is to permanently seal greenhouse gas ("GHG") emitting wells reliably and economically by utilizing a low melting point bismuth-tin alloy, molded *in situ*, as the well casing and cemented annulus sealing material.

The bismuth-tin alloy that Seal Well uses as a sealant has the following fundamental properties that make it a superior material for blocking gas leakage from wells:

- The molten alloy expands volumetrically by about 1% as it solidifies.
- The alloy has a high specific gravity of 8.7 such that it displaces other wellbore or annular fluids that may be present and does not mix with them.
- Because the molten alloy is a non-particulate single phase, it can be squeezed through casing perforations and into whatever permeability exists in the wellbore wall rock where it solidifies and seals.
- The low viscosity molten alloy flows readily into narrow fissures, fractures, and channels.
- The alloy is a low melting point (138^{o}C) eutectic which can, therefore, be melted *in situ* without harming well casing or annular cement in the vicinity.
- The solid alloy has a compressive strength of 55 MPa.
- The solid alloy has a Brinell Hardness of 23, and, therefore, can be milled readily from casing.

Figure 1 below illustrates the equipment Seal Well used in deployment of the bismuth-tin alloy in this project. An electrical resistance heating tool is lowered on a mono-conductor electrical wireline cable as commonly used by oilfield service companies for operating perforating guns or logging tools. Depending upon the particular heating tool design, the solid alloy is carried within the tool surrounded by a heating element or the alloy is cast on the outside of a cylindrical cartridge type electrical heater.
Figures 2 and 3 are photographs of the two types of heaters used in this project.

Seal Well has trailer mounted generator and power control equipment for powering the heating tool. Three phase 480V power is generated and fed to a variable voltage controller, a multi-tap three phase transformer, and an AC to DC converter to produce DC current at a voltage needed to provide sufficient power to the heater to melt the quantity of alloy being deployed. For field application, we connect our power supply to the cable spooled on a wireline truck supplied by a third party service company.

For creating a casing plug for routine well abandonment in Alberta, a mechanical bridge plug is first set by wireline at a depth within 15 meters of the top-most production perforation. The Seal Well heater is then lowered into the well to rest on the bridge plug and power is applied to melt the bismuth-tin alloy. Once the alloy is fully melted, power is turned off, and the heater is raised above the molten alloy pool to allow the alloy to cool and solidify by thermal conduction to the surrounding earth. Usually modest pressure is applied by a surface water pump during the cooling/solidification process in order to enhance the seal formed by the expanding alloy by encouraging expansion in the radial direction.

The procedure used for SCVF repair is similar except that the well casing annulus must be perforated, slotted, or section milled to provide conduits for molten alloy to be "squeezed" into the annulus and wellbore wall to interdict and seal channels that are carrying gas to the surface within the leaking well annulus. In the SCVF repair case, more heating is required in order to raise the temperature in the radial direction above the 138°C alloy melting point to assure that the alloy remains in a molten state until it reaches at least the wellbore wall. In addition to the use of an effective sealant material, successful SCVF repair in a given well depends very importantly on accurate location(s) of the source(s) of the leaking gas, the location of the repair squeeze relative to the surrounding geological formation, and the method by which the annulus is accessed. These most important topics are addressed more thoroughly later in this report.

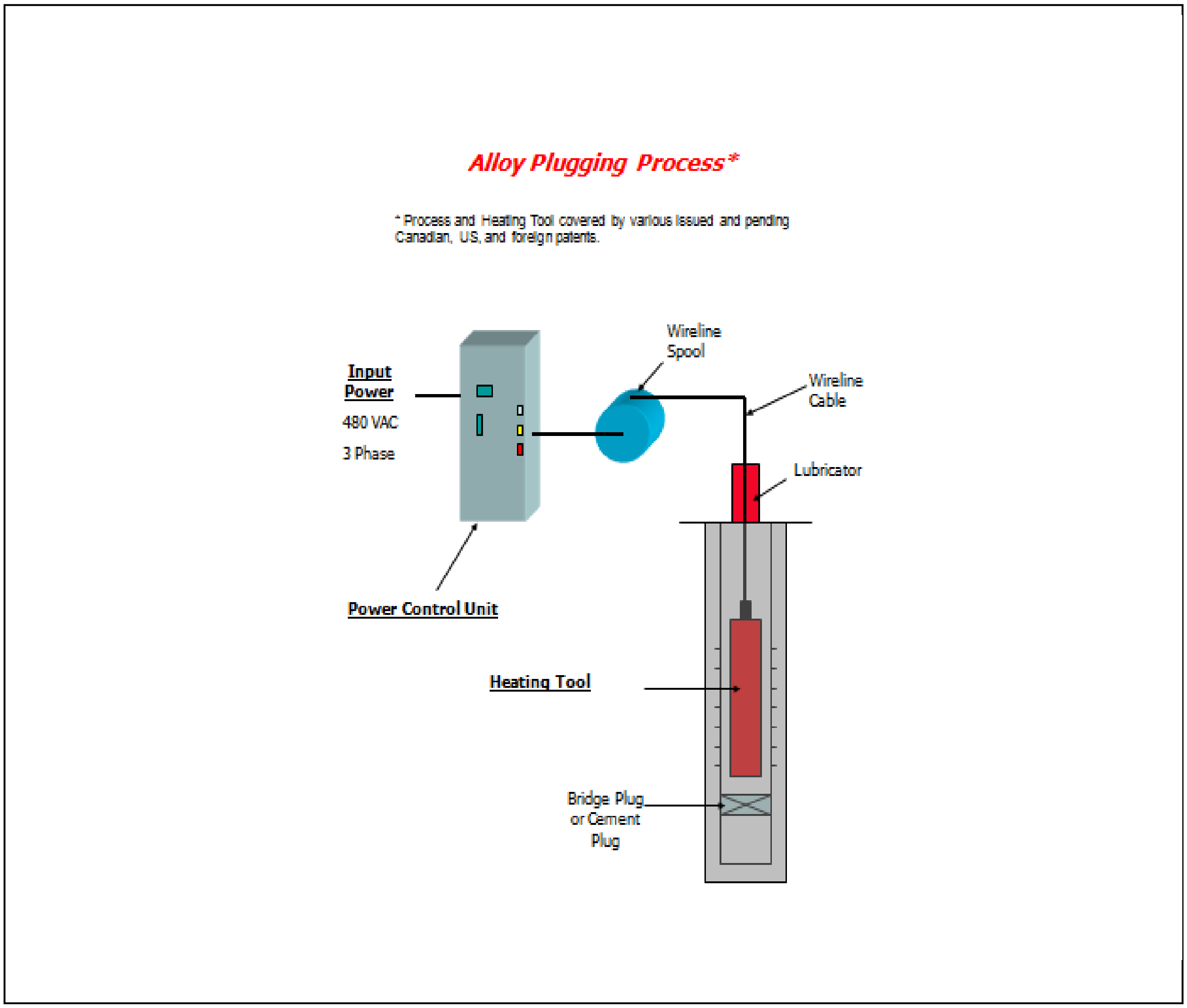

Figure 1. Seal Well Alloy Deployment Process

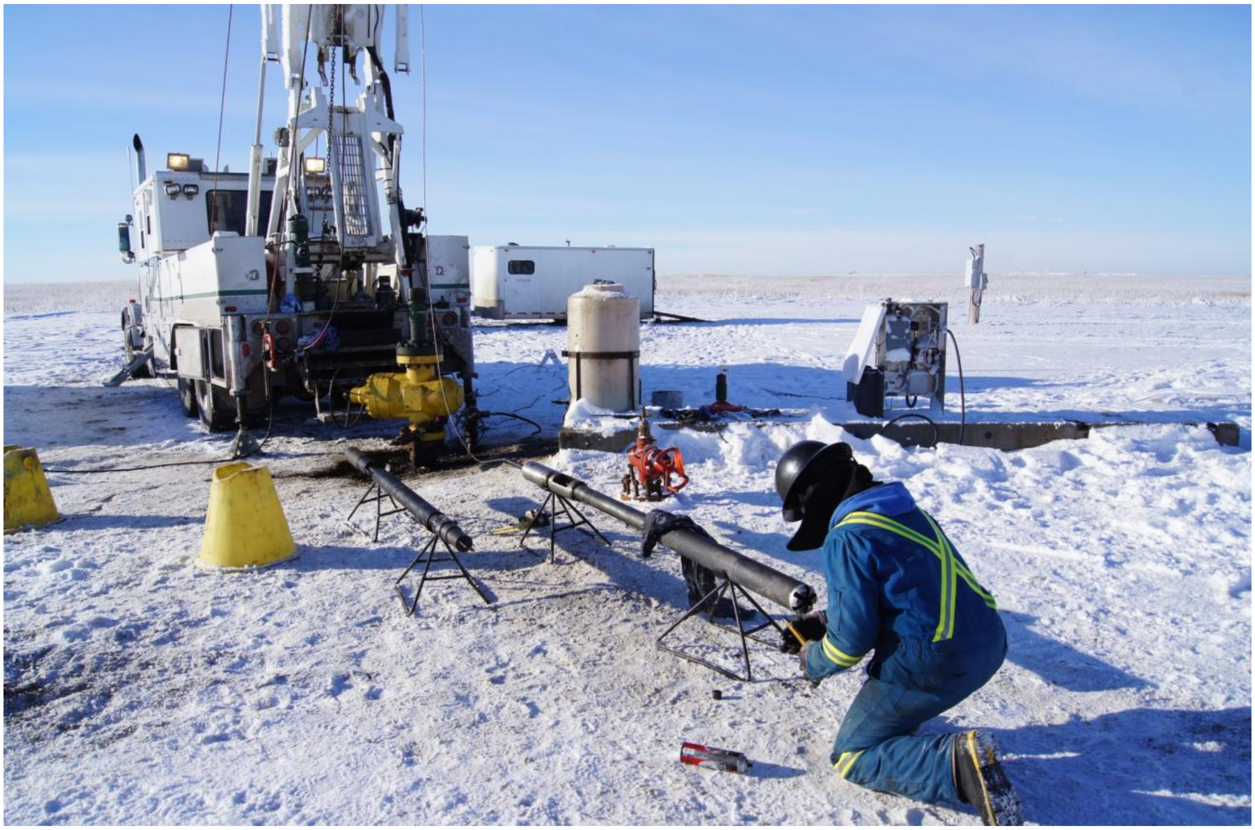

Figure 2. Seal Well hollow alloy deployment heater and associated equipment

Figure 3. Seal Well alloy deployment tools with alloy cast on the outside of a cartridge heater

3. Project Goals

The goals for this project were as follows:

- Investigate the fundamental properties of the bismuth-tin alloy that are relevant to the use of this material in sealing oil and gas production and CO_2 sequestration wells in Alberta;
- With instrumented physical model and complex numerical computer techniques, develop and test tool designs and procedures to accomplish economical and successful deployment of the alloy in field trials;
- Test the material, tools, and procedures developed in actual leaking wells to confirm their effectiveness for the intended sealing;
- Analyze all the testing results to aid further commercial development of the technology.

4. Work Scope Overview

In order to successfully introduce any novel technology to the oil and gas upstream industry, one must be able to answer basic questions:

- Does it work for the purpose intended?
- Does it work better or more reliably than traditional methods of addressing the problems?
- Is it economical relative to other methods of solving the targeted problems or applications?
- Are there troublesome side issues associated with its use that do not exist with traditional methods of addressing the same problems or applications?

The use of a metal as a sealant in well environments, especially those where acid gases CO_2 and H_2S are present, raises corrosion concerns that must be defined. Dissimilar metals immersed together in an electrolyte can set up a galvanic cell and currents that dissolve one metal relative to the other. In our case, the metals are the carbon steel of the well casing and the bismuth-tin alloy. The electrolyte is the water or brine that fills the well during and after the plugging procedures. Also, chemical reactions between the alloy and its environment need definition and measurement at relevant temperatures, pressures, and pH values.

For use of a given sealant in GHG sequestration wells, the material should have a service life long enough to contain the sequestered gas to remain in place until it becomes chemically fixed as a solid. Designers of sequestration projects are seeking a sealant service life of three thousand years for this purpose. CO_2 dissolved in water produces carbonic acid, and H_2S in water produces sulfurous acid, both of which attack cement and the nitrile elastomer commonly used as a mechanical bridge plug seal. Clearly, those materials, even though approved for use by the Alberta Energy Regulator for routine casing abandonment, are inadequate for sealing CO_2 injection and other wells penetrating the geologic formation used for sequestration of GHG.

Seal Well contracted with the University of Calgary to design and perform the comprehensive corrosion testing that defines the service life expected for bismuth-tin eutectic alloy plugs. The study was led by Professor Viola Birss and her colleagues in the Chemistry Department. A detailed report on the corrosion study is included in Appendix A, but the results show that bismuth-tin eutectic alloy plugs can be expected to have a service life in the specified wellbore environments substantially longer than the three thousand year target.

Despite the common usage of the word "bond" in the industry (as in "bond logs," for example), no physical bonding is achieved by any of the sealants presently used to prevent well leakage, whether it be cement, polymers, resins, elastomer bridge plug seals, or bismuth alloy. Effective sealing is determined by the residual radial stress that remains between the sealant and the surface being sealed after the deployment procedure has been completed. Hence, a measure of physical stresses that are induced in well casing during the heating/melting/solidification/cooling cycle involved in the alloy deployment are necessary to be assured that a seal can actually be expected at the end of the procedure. Also, in the case of bismuth alloy, the *in situ* melting is an unsteady state heat transfer process that requires quantification in order to design tools and to determine operating parameters that are used in the field testing of the procedures involved. Computer software packages are available that are capable of solving simultaneously the complex differential equations that describe the various physical processes in play, and the use of one such is the most expeditious way of determining the feasibility of the procedures under development. Seal Well licensed the multiphysics program, COMSOL, for this purpose and engaged AltaSim Technologies, a consulting firm expert in formulation of such mathematical models, to assist in this task.

Testing in instrumented full-scale physical models is also desirable in order to confirm operating parameter values computed by the classical equations in the mathematical model. The testing of physical models was carried out in Seal Well's shop and in the shop of a wireline service provider.

The final milestone in this project was the field testing of the sealing tools and procedures in at least three wells that exhibit greenhouse gas emissions. This report describes tests in eight such wells: three wells to test internal casing plugs for routine abandonment purposes and five wells to test annular sealing procedures to block GHG leakage through the wellhead vent.

Outcomes and Learnings

1. Literature Review

Much has been written about the incidence and causes of leakage from oil and natural gas production wells and, in addition, procedures and case studies that involve principally Portland cement as a sealant. A lesser number of papers cover use of resins and polymers as sealants. There are extensive studies in the literature regarding the toxicity (or lack thereof) of the bismuth-tin eutectic alloy in contact with fresh water. The focus of the toxicity studies was related to finding a non-toxic substitute for lead shot for waterfowl hunting, and, as a result, the bismuth-tin eutectic alloy shot is sold commercially for that purpose. There is very little in the technical literature regarding the corrosion of the bismuth-tin eutectic in environments resembling those of oil and gas wells. The bismuth-tin eutectic alloy was first formulated in the early 20th century as one of several bismuth-based alloys used mainly as low melting point solders and fuse material. The physical properties of these alloys are well-known, and tabulations are readily available on the websites of their several world-wide commercial suppliers.

2. Technology Development

The development of this technology began with our introduction to the unusual properties of bismuth and its alloys. We were familiar with the common problem in Alberta and elsewhere of persistent gas leakage from wells. The fact that pure bismuth expands when it solidifies from a molten state by about 4% suggested that it or its alloys might act as an interesting sealant if it could be deployed readily in wells. Our focus rapidly narrowed on the 58 wt% bismuth – 42 wt% tin because, as a eutectic mixture, it melts and solidifies at a convenient temperature of 138^oC as opposed to pure bismuth that melts at 271^oC. Of all the bismuth alloys, the bismuth-tin eutectic expands most upon solidification (about 1%), its measured bond strength against steel was best (and 5 times better than Portland cement), and its lack of toxicity had already been thoroughly tested.

We had been involved previously in developing and testing electrical heaters used for stimulating production of heavy oil. The design and building of power control equipment and heaters to melt and deploy the bismuth alloy were more straight-forward in comparison.

Growing concern over global warming and the contribution of greenhouse gas emissions to the problem provided further impetus to the development. Sequestration of CO_2 by injection into depleted saltwater containing geological formations gained momentum as a possible mitigating technology, but permanent containment of the acidic gas is an obvious issue. The carbonic acid formed by solution of CO_2 in water and in contact with other minerals will eventually be fixed by conversion to carbonate rock, but the reaction is very slow, and thousands of years are thought to be required for the reaction to be complete. Meanwhile, carbonic acid attacks cement, the common sealant in both CO_2 injection wells and in abandoned hydrocarbon wells likely to exist in the sequestration formation. A preliminary corrosion study of the bismuth-tin eutectic in a CO_2 sequestration environment was promising, but was too incomplete for serious consideration of the alloy as a sealant in this application. A more comprehensive corrosion study would be a necessary first step.

We were further encouraged in this development when, as related above in the Introduction section of this report, the Alberta Energy Regulator changed their Directive 020 rule to require that plugged and abandoned wells remain open to the atmosphere at surface, essentially implying thereby that the approved abandonment procedure of dump bailing cement on top of a bridge plug is an unreliable method of preventing GHG leakage from depleted hydrocarbon bearing formations up the casing and out the newly mandated vent. Well cement is known to shrink slightly as it sets and is, therefore, prone to allow gas leakage. Mechanical bridge plugs have elastomer seals that degrade with time and are also eventually likely to leak[19]. If we could prove that a modest plug of bismuth-tin eutectic alloy would hold sufficient pressure and if the results of a relevant corrosion study of the alloy were favorable, then it would seem that inevitable eventual leakage of greenhouse gas from the enormous number of existing and future Alberta wells could easily be avoided.

Gas leakage through the annulus between the wellbore wall and the outside wall of production casing and out the annulus vent (“SCVF”) presents a more complex sealing problem. The annulus is not wide, measuring an inch or so, and is typically filled with cement. However, channels can be formed along the outside surface of the production casing, the inside surface of the wellbore wall, within the cemented column between the two walls, or all three locations. The channels can be formed during the original completion of the well because of the shrinkage of cement or its weak transition phase as it sets. Channels can be formed also long after the original well completion work due to a variety of possible mechanical shocks during the production process. The channels can be almost microscopic in diameter and still conduct significant gas flows[19].

Alberta Energy Regulator rules require that SCVF must be repaired either before a well is put on production, in case of “serious” gas leakage, or before the well is plugged and abandoned, in the case of “non-serious” leakage. Also, the leak should be repaired as close as possible to the geological source of the leaking gas. A given well can penetrate more than one gas bearing formation, each of which may contribute to the leak flow. A well with a non-serious SCVF can be operated for many years, and permeable formations above the source can become charged with gas, which, in turn, can cause an ambiguous repair result due to the discharge of absorbed gas.

In recent years, noise logging technologies have significantly improved the ability to detect and locate individual gas leakage sources. Cased hole logging techniques have been developed to detect hydrocarbon presence in formations after a long period of production. Comparison of the cased hole log with the original open hole log performed before completion of the well helps to distinguish source zones from subsequently charged zones.

Another issue with SCVF repair is the selection of the method of accessing the well annulus. The methods available are high density perforations, slotting with abrasive jetting, complete milling of a section of casing, and, most recently, slot perforating. Each method has advantages and issues. Each has proponents, and each has a lesser or greater capital cost. At a minimum, whatever access method is used must guarantee opening the annulus over a distance at least equal to the circumference of the wellbore in order to have a statistically good chance of interdicting the leakage channels over the length of the accessing zone. Complete circumferential milling of a section of casing and its surrounding cement guarantees channel interdiction, but the procedure is expensive and has potentially troublesome side issues. Abrasive jetting of a spiral slot in the casing appears attractive, but it is an expensive procedure, and there are industry reports that location of the slotting may not be precise. Seal Well has used less costly high density perforation in field tests with good success, and more recently introduced slot perforating is perhaps an even better choice for alloy squeezing.

The next issue is the location of the repair relative to the source of the gas. Gas in a given porous and permeable geologic formation has remained in place over geologic time by a cap rock formation with very low porosity and permeability. SCVF occurs because the cap rock formation is penetrated by drilling the well, and the annular cementing has not succeeded in preventing gas flow from the source for the reasons stated above. The most logical location for repairing the SCVF is within the cap rock using a sealant that is capable of forming a tight seal against it. The traditional sealant used in Alberta and elsewhere is cement, but cement is not capable of reliably sealing against the cap rock because it shrinks slightly. Therefore, the most often recommended traditional SCVF repair procedure is to access the gas source formation just below the cap rock and to pump cement into its permeable structure to the extent that the formation continues to accept it, sometimes even fracturing the formation in the process. However, cement is a two phase fluid of a solid in suspension in water. Inevitably, the water phase travels further into the porous medium of the formation in an uncontrolled way, and there is no way to know the quality of the cement plug that results. Fracturing the gas source formation is inherently a process with less than ideal controllability, and may add to the difficulty of sealing the gas leak.

Because of the uncertainties listed above, SCVF repairs in Alberta and elsewhere are characterized by multiple attempts being required with costs mounting to hundreds of thousands of dollars for individual wells. The use of a sealant like the bismuth-tin eutectic that can be deployed in molten form and allowed to solidify, expand, and therefore form a strong seal against an impermeable cap rock eliminates one major uncertainty with SCVF repair.

3. Corrosion Study

The complete detailed report of the bismuth alloy corrosion study has been prepared by the Birss Group at the University of Calgary and is contained in Appendix A where it is made part hereto. Their report shows that the bismuth-tin eutectic passes muster in every way for the applications we intend, including the requirements for permanent abandonment sealing for North Sea wells as defined by the NORSOK Standard D-010, and we will leave it to Professor Birss and her colleagues to present the evidence in their own words.

4. Computer Model Mathematical Simulations

Mathematical models are useful in projects like the present one to aid in the understanding of the importance of particular physical parameters in the successful functioning of the process being developed. The measurement of some parameters is difficult or excessively expensive to obtain directly with physical models.

The Seal Well process for deployment of bismuth-tin eutectic alloy plugs and seals involves unsteady state heat transfer in the *in situ* melting and subsequent solidification of the alloy. The strength of the sealing achieved is determined by the resultant stresses after the expansion with heating of the materials involved, the contraction of the materials as they subsequently cool, and the volumetric expansion of the alloy upon solidification. The heat transfer computations can be validated readily by measurements taken during physical model testing. The stress analysis measurements in a process like this are much more difficult.

Since the form of a well is cylindrical and that of Seal Well's heating tools is cylindrical also, the appropriate models can be formulated with axial symmetry and, therefore, two dimensional. This simplification makes the solution of the three dimensional problem less time consuming to solve. Figure 4 below shows the results of a computation of the temperature profiles developed by the heating process under one value of heat input rate and duration. The computation system used is COMSOL Multiphysics.

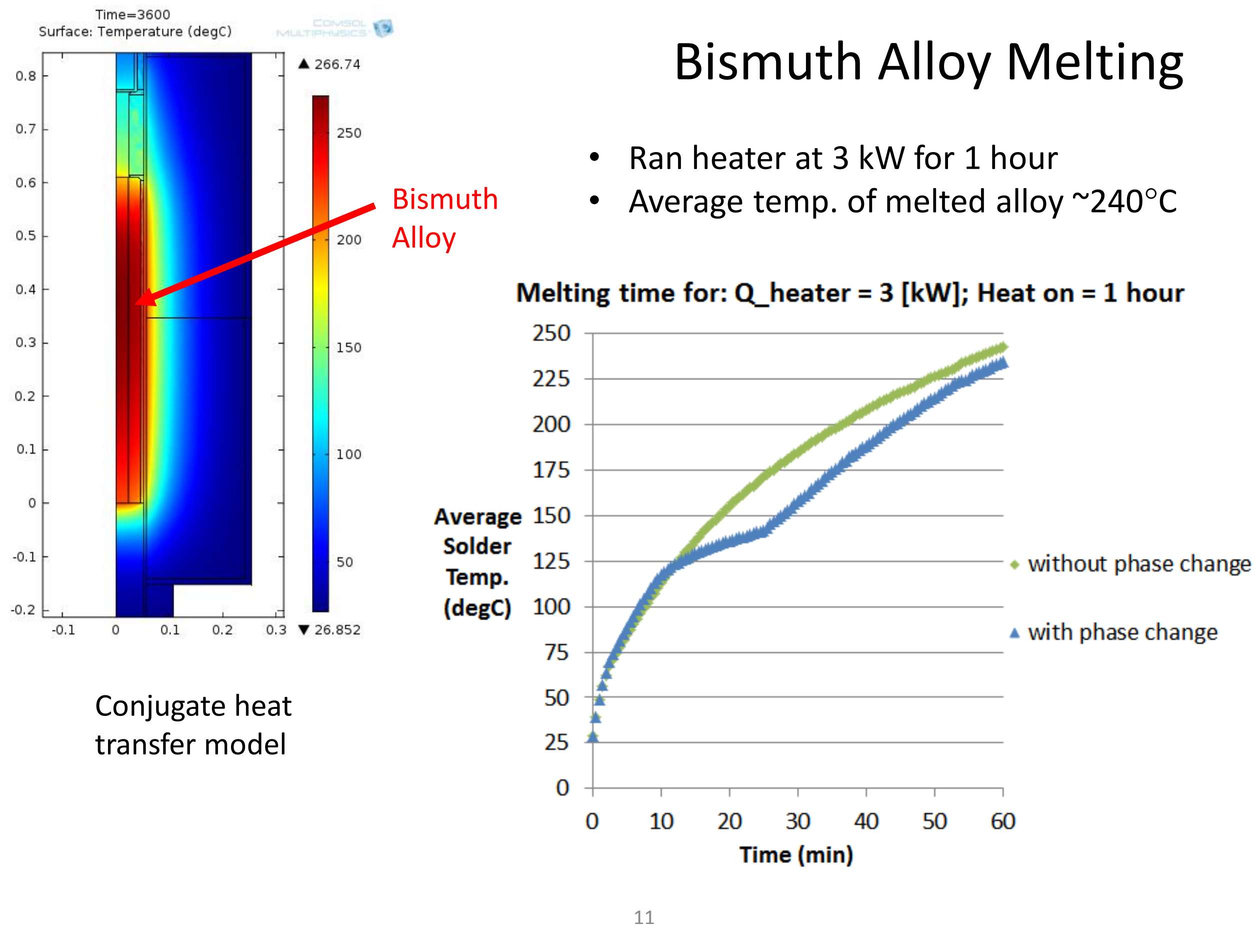

Figure 4. Computed Temperature Profiles for 4-1/2”- 16” Casing Model Test

An example of stress analysis computation integrated with heat transfer considerations is the evaluation of the sealing strength of a bismuth alloy casing abandonment plug as a function of aspect ratio (plug length/plug diameter). How much alloy must be deployed in 4-1/2” OD casing as a plug to meet the AER hydraulic pressure test for abandonment of 7 MPa minimum? Figures 5 through 7 below show the results of that computation.

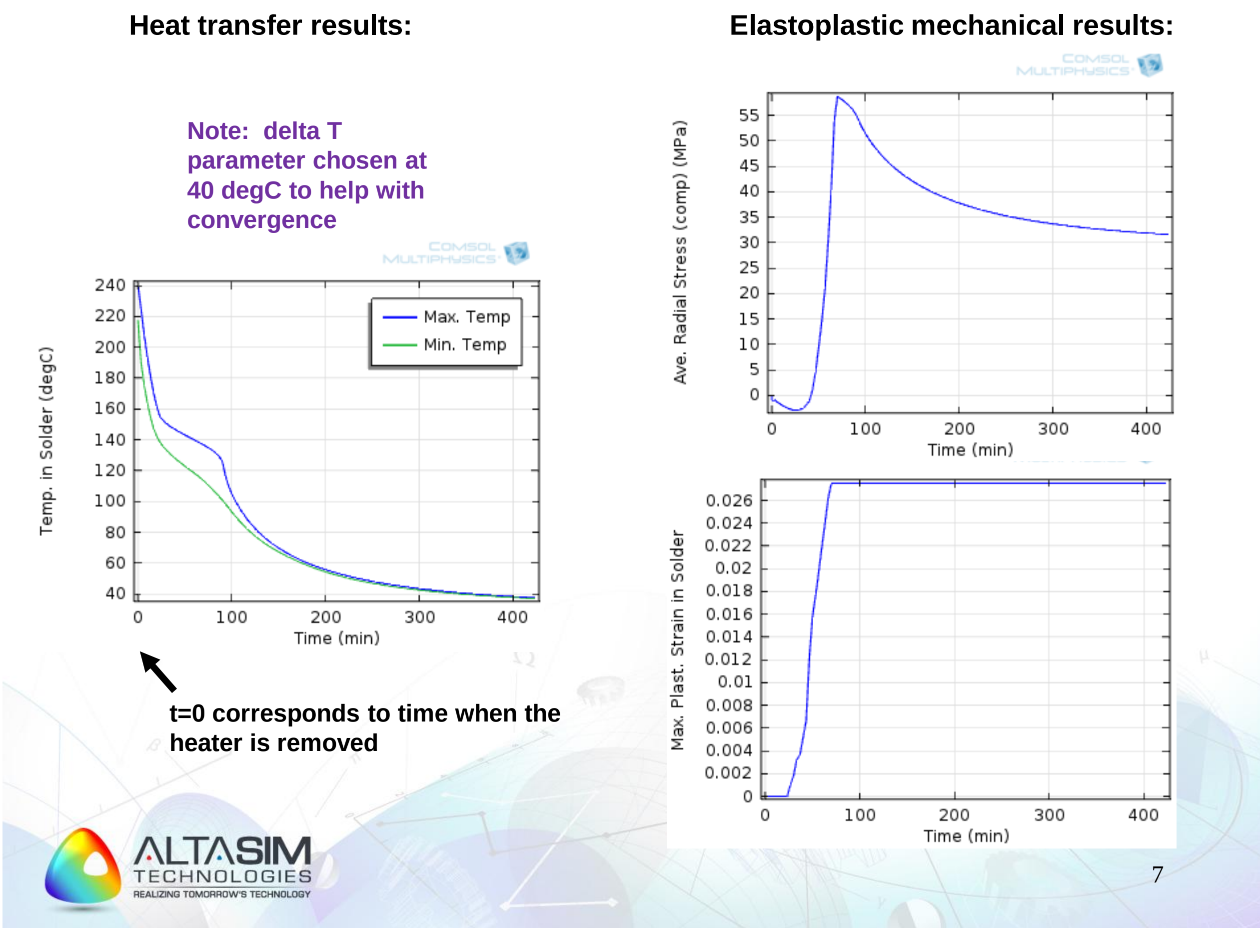

Figure 5. Temperature and Stress Profiles for a Bismuth Alloy Abandonment Plug in 4-1/2" OD Casing

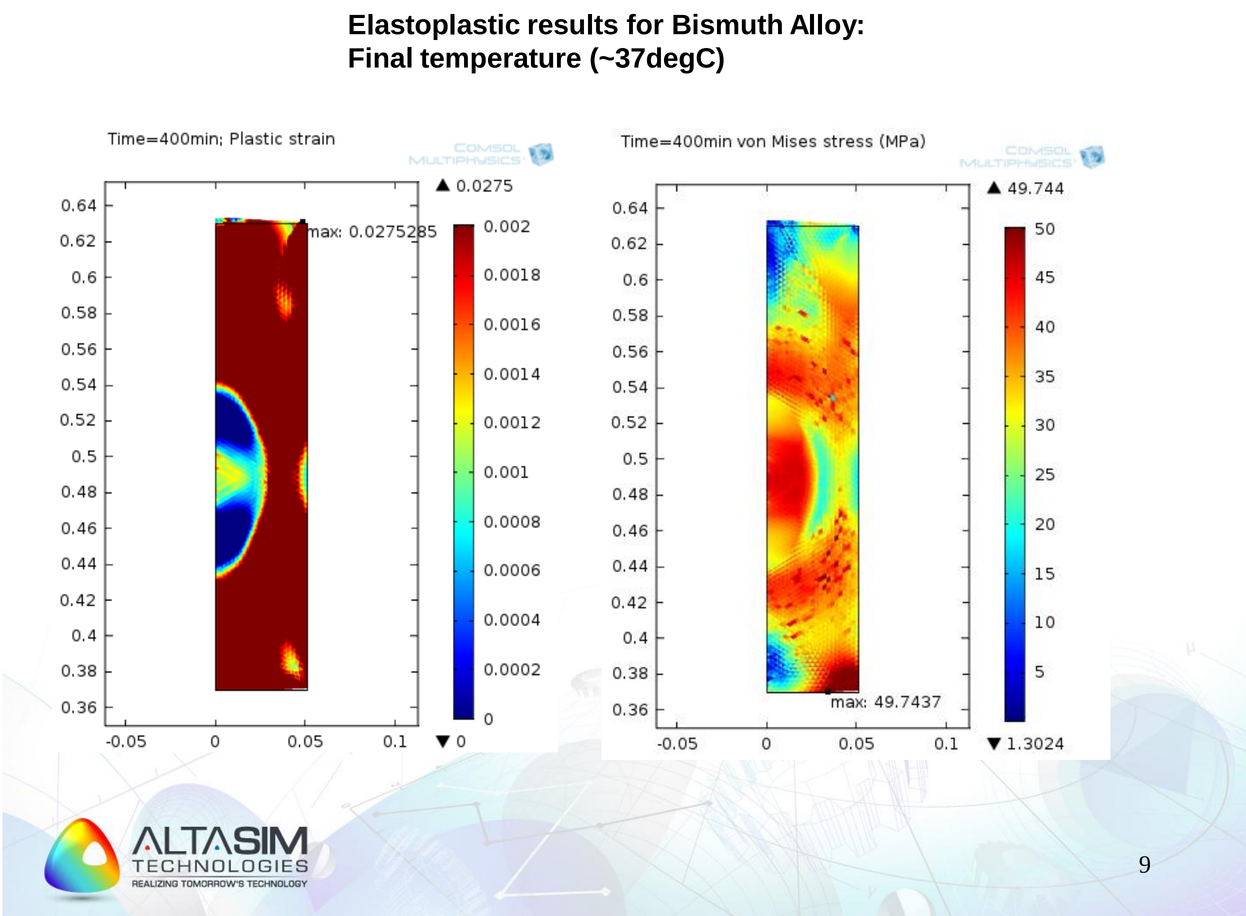

Figure 6. Stress Map for Abandonment Plug in 4-1/2" OD Casing

Bismuth Alloy Abandonment Plug Calculated Strengths

Assumptions: (1) Alloy/steel coefficient of friction reduced 80 % by wellbore fluid wetting
(2) Dry coefficient of friction between alloy and steel surface is 0.61
(3) Residual radial stress at the cooled alloy/steel interface is 30 mPa

Plug Length, in.	Plug Aspect Ratio, L/D	Max Dry Strength, mPa	Max Wet Strength, mPa
12	3	220	44
16	4	293	59
20	5	366	73
24	6	439	88
28	7	512	102
32	8	586	117
36	9	659	132

10

Figure 7. Computed Bismuth Alloy Plug Strength vs Aspect Ratio

5. Physical Model Studies

Several physical models were constructed from steel well casing of various diameters in which bismuth-tin eutectic alloy plugs were deployed under simulated field conditions in order to measure the strength of the plugs and the heat transfer parameters associated with the deployment process. Figure 8 is a photograph of one such model in which the strength of a bismuth alloy casing abandonment plug was measured.


Figure 8. Casing Abandonment Plug Test Cell

Figure 9. Casing Abandonment Plug Test Pressure

The 4-1/2” OD test cell was constructed such that nitrogen gas could be introduced sequentially to both sides of the plug as required by international standards for testing casing plugs. Figure 9 is a photo of the gauge measuring a 13 MPa (1800 psig) test pressure during one such test. Pressure tests on this and similar test deployments were conducted at about monthly intervals for a period of more than two years without an incidence of failure recorded. Figure 10 is a photograph of a cross-section of a bismuth alloy plug set within a water filled test model that shows the apparent quality of the seal between the steel casing and the alloy plug.

One of the important considerations in achieving good results in SCVF repairs is the method of accessing the leaking well annulus. Since the number of channels and their radial and circumferential location cannot with certainty be determined by logging techniques, access to the entire wellbore circumference should be assured by whatever access method is chosen. The most convenient and least expensive method is high density perforation using a gun such as Owens’ “Uzi” which shoots 118 0.22” diameter holes in a spiral pattern over a 1 meter interval, We hoped to test this method in two of our physical models by shooting them within a test bunker at Owens’ facility in Red Deer in order to determine the extent to which the annular cement is shattered by the explosive charges. These two tests failed, however, because the models could not be fixed sufficiently within the bunker to cause the perforation to succeed. The energy of the explosive charges was dissipated by lifting the models rather than shooting holes in the steel casing.

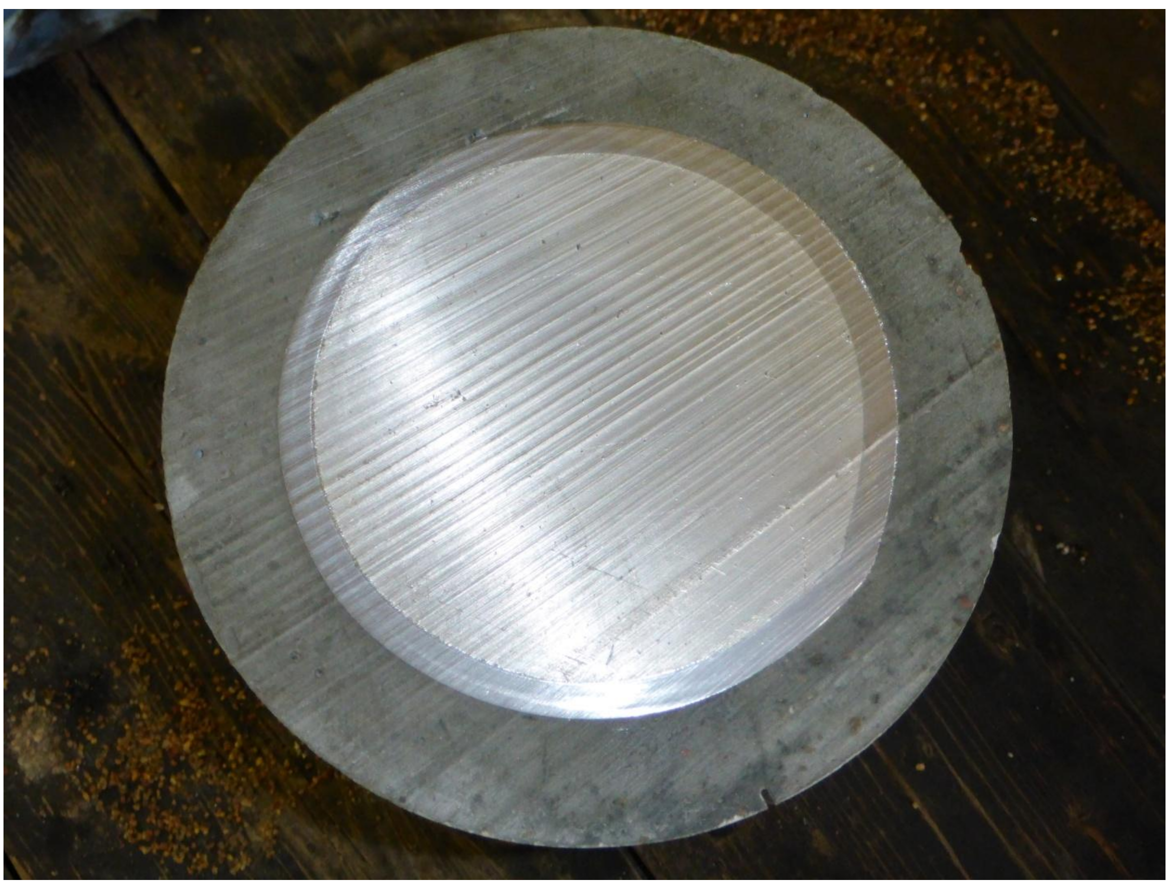

Figure 10. Cross-section of Bismuth Alloy Plug in 5-1/2” OD Casing with External Annular Cement

Figure 12 below is a photograph of another one of the physical models used in our testing. This model was comprised of 4-1/2” OD well casing inside 16” OD casing. The annulus between the two casings was filled with Class G well cement, and a series of ¼” OD holes to simulate perforation tunnels were drilled through the larger casing, the cement, and the smaller casing. The entry holes in the larger casing were sealed by welding. A heating tool with externally cast alloy similar to that shown in Figure 3 was inserted into the smaller casing, and the model was lifted into the vertical. The inner casing was filled with water and was pressure sealed around the connecting electrical wireline cable using a lubricator. A pressure regulated nitrogen source was connected to the model in order to maintain a constant interior pressure of 1000 psig. An array of thermocouples was attached to the outside surfaces of the casings to measure the changing surface temperatures during the melting and deployment of the alloy.

The objects of this test were to melt and squeeze the bismuth-tin alloy into the perforation tunnels under heating and other physical conditions as close as possible to those that pertain to actual wells undergoing SCVF repair, to compare measured temperatures to those predicted by mathematical model computations, and to demonstrate that the molten alloy would fill the perforations to a radial distance at least that of the wellbore wall in an actual well cased with 4-1/2”OD casing. Electrical heating was applied at the rate of 3 KW for a period of one hour. The heating tool was lifted out of the pool of molten alloy produced, and the alloy was allowed to cool and solidify while maintaining pressure on the model assembly. Figure 12 is a photograph of a cross-section of the model cut through both casings, the annular cement, the alloy plug, and one perforation tunnel. This demonstrates that the molten alloy displaced water within the perforation to a radial distance of about 4 inches under the heating protocol used in this test. This distance is about 4 times that normally required to penetrate through the cemented annulus and into the wellbore wall in most Alberta well completions. The penetration distance of the molten alloy is a function of the heating rate and the time over which the heating is applied. More heating results in an increased temperature profile in the radial direction and a deeper penetration of the alloy before it solidifies.

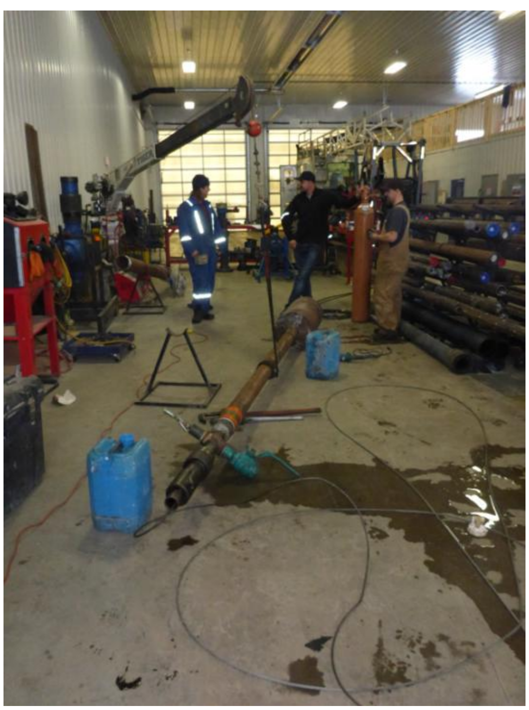

Figure 11. Preparation of 4-1/2”-16” Casing Model for Testing

Figure 12. 4-1/2”-16” Physical Model Cross-section with Alloy Filled Perforation

The temperature data from surface mounted sensors on the physical models and from a recorder within the heating tools agreed very well with the profiles obtained from the mathematical model runs. This agreement provides confidence in the calculated results such that they can be used to guide the heating protocol used for individual field jobs on wells with differing casing sizes and depths. The interior heating tool temperature profile provides, in addition, a qualitative picture of phase change and fluid flow during the squeezing job to aid subsequent analysis. As an example, Figure 13 below is a temperature log from a recorder located about two feet above the heating elements in the tool being used to melt and squeeze bismuth alloy into perforations in ConocoPhillips Well 14-029-046-5W5. The first part of the profile shows the heating and melting of the alloy. The next steep section indicates the heating of the molten alloy to a maximum value whereupon the alloy flows into the annulus. The temperature decline highlighted in red is indicative of relatively cold fluid from a channel located between the annular cement column and the wellbore wall being displaced by the molten alloy into the interior of the perforated casing. When the heating tool was subsequently removed from the well, we found it coated in heavy oil presumably from a formation located at or just below where the alloy squeeze took place. The cement bond log in this region of the well gave no indication of the existence of this channel. The last part of the temperature profile shows the cooling and solidification of the alloy once power was removed from the heating tool.

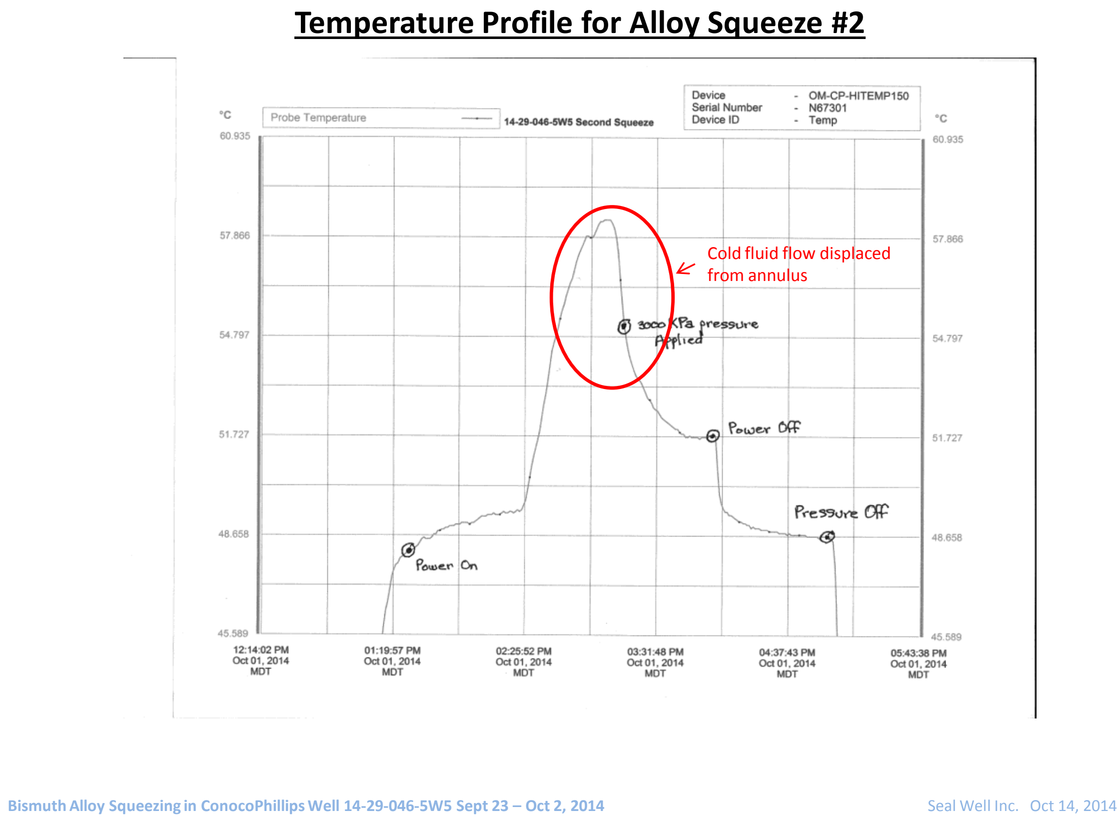

Figure 13. Heater Interior Temperature Log

6. Installation Process

The Seal Well bismuth alloy deployment process is pictured in simplified form in Figure 1 and is generally described in Section 4.2 above. Figure 2 is a photograph of an SCVF repair being prepared for execution. In the foreground, a field engineer is loading a heating tool with solid alloy. The heating tool is connected at its upper end to the mono-conductor wireline spooled on the service truck pictured. In the background is a trailer that contains an electrical generator, voltage control devices, and an AC to DC converter. The output from the electrical generation and control equipment is connected to the other end of the wireline cable and is conducted by the cable to power the heating tool. To the right in the photo is pictured a continuous vent flow and pressure recording device. This photo was taken at the Weyburn, SK well site where the successful SCVF repair described further in this report took place.

The amount of alloy to be deployed on a given job is determined by prior analysis of logging and other data available for the well in question. A computation is performed to determine the heating rate and time to be employed, and a field procedure is provided to the client for approval. A general procedure for SCVF repair is as follows:

General Procedure for Squeezing Bismuth Alloy

1. Locate source of vent gas leak as accurately as possible.
2. Select the annular zone which will receive the bismuth alloy squeeze. This will usually be the first low permeability layer above the source of the leaking gas.
3. Set a bridge plug immediately below the target zone.
4. Perforate well casing over a length of 0.3 to1.0 meters using a high shot density, but low penetration charge.
5. Pour sand or grit into well to fill the casing volume between the top of the bridge plug and the bottom perforation.
6. Fill well with water.
7. Load Seal Well Alloy Melting Tool with alloy, connect to wireline, and RIH through lubricator.
8. Tag bridge plug for depth confirmation and record.
9. Pick up slightly to recover the weight of the Seal Well Alloy Melting Tool.
10. Close vent valve, but monitor annular pressure, if possible.
11. Apply power to Seal Well Alloy Melting Tool. Continuously monitor tool weight to determine completion of alloy melt and heating of the well annulus and wellbore wall.
12. Open vent valve.
13. Apply squeezing pressure at the surface by pumping with an accurate gauge or approximately 15 minutes while power is still being applied. Pressure should be determined in advance to be below the fracture gradient of the zone receiving the repair.
14. Shut down power and lift Alloy Melting Tool a few meters, but continue application of pressure at surface for approximately one hour.
15. Remove Alloy Melting Tool from hole.
16. Wait approximately 2 hours with heating discontinued before checking the alloy level.
17. If the alloy level has not reached above the top perforation, re-load the Alloy Melting Tool and repeat the melting and solidification procedure.
18. Apply 7 mPa pressure to test the alloy seal, if appropriate.
19. If the well is to continue in operation, remove the solidified bismuth alloy from well casing with a milling tool, circulate out any sand added, and remove the bridge plug.

The procedure for deploying a bismuth alloy casing abandonment plug is similar, but the casing need not be perforated or the molten alloy squeezed. A mechanical bridge plug is set at the appropriate depth to serve as a platform on which the molten alloy is deployed and allowed to solidify. A length/diameter aspect ratio of no more than 4 to 1 should be sufficient to withstand a 7 MPa hydraulic pressure test required by AER regulation.

7. Field Test Outcomes

a. Cenovus Wells 14-11-019-11W4, 16-02-016-15W4, 08-26-019-12W4

These three are shallow gas wells in Alberta in the vicinity of Brooks. An earlier attempt had been made to set casing abandonment plugs in these three wells, but the plugs did not pass hydraulic pressure tests and, therefore, leaked gas. An application was made by the operator, Cenovus, to the AER to allow us to melt bismuth alloy on top of the existing plugs as a platform to determine if a 4/1 aspect ratio alloy plug would withstand the required 7 MPa hydraulic pressure. The AER approved with the condition that the wells remain open for at least 6 months after the setting of the alloy plugs and be pressure tested again before cutting and capping to complete the abandonment procedure.

The alloy plugs were set and successfully passed the initial pressure test. The wells were re-visited after 6 months and again successfully passed the 7 MPa pressure test.

b. Cenovus Wells 16-08-006-13W2, 12-08-006-13W2, 08-03-006-14W2

These three wells are located within a CO_2 flood project operated by Cenovus near the town of Weyburn, SK. All three wells exhibited measured gas leakage through the wellhead vent. After thorough consultation with Cenovus operations engineers, Seal Well performed bismuth alloy squeezes on all three wells at agreed upon depths. The squeezes resulted in an immediate dramatic SCVF reduction from all three wells, and subsequently the SCVF ceased totally. We are advised by Cenovus that casings in all three wells now have been cut and capped.

The 08-03-006-14W2 well presented a new challenge that warrants special comment. This well contains 5-1/2" OD casing whose annulus was not cemented to surface. The production perforations in the well had previously been filled with cement, but the level of cement within the casing from the cement squeeze was substantially higher than the cement level in the annulus. Therefore, the annulus into which Cenovus asked us to deploy bismuth alloy contained either water and/or old drilling fluid at the alloy squeeze location. It was certainly possible that molten alloy injected into a water-filled annulus might merely disappear down the annulus and never fill the alloy squeeze perforations.

We ran a simple test in our shop of pouring molten alloy into a perforated pipe that was immersed in water. Figure 14 below is a photograph of the result of this experiment. The molten alloy flowed through the perforation, but almost immediately froze to the outside surface of the pipe. As more molten alloy flowed through the perforation, it froze on top of the earlier solidified alloy, and a deposit built upon itself much in the way an icicles forms. It appeared that this mechanism would result in an alloy platform being built such that the well annulus could be sealed without a perforated cement structure to hold it. Cenovus agreed that we should try this in the well, and it worked!

Figure 14. Build-up of Annular Alloy Plug

c. ConocoPhillips Well 14-29-046-5W5

This well is in the Pembina Field near Buck Lake, AB. It was completed in the Belly River formation with perforations at 1095-1100 mKB, 1138-1144 mKB, and 1163-1167 mKB. Cement was squeezed into the three original perforated intervals and one additional interval at 1156-1158 mKB. Another three cement squeezes were performed at shallower zones in the 625-788 mKB interval. Nevertheless, the well exhibited a persistent SCVF with an ambiguous source. A cased hole neutron density log was run which revealed more than thirty gas shows from the original production zone to the bottom of the surface casing.

The client nominated the interval 1129.0-1129.6 mKB for performing the bismuth alloy squeeze. This depth was based upon its being above the second Belly River original production intervals in a zone with an excellent cement bond according to the bond log. Since cement bond logs indicate the state of the cement/casing interface and possibly the existence of a void space within the cement column, and the bond as indicated on the log appeared to be perfect, the gas leaking channel at this depth in this well was probably between the cement and the wellbore wall.

A Doull vent meter that measures either gas flow or annular pressure at surface was installed on this well during the alloy squeezing operation. The leak rate measured was about 7 m^3/day. Three alloy squeezes were performed within the perforated interval in order to fill the annular space and to cover all perforations. During the operation, heavy oil was noted covering the Seal Well heating tool indicating that the channel at the wellbore wall contained the oil that was displaced as the channel was filled by molten alloy. A material balance calculation on the alloy deployed indicated that the leak channel volume equaled 17% of the total annular volume over the perforated interval. The vent meter showed that the SCVF rate had been affected by the alloy squeeze, but the gas flow was not shut off entirely during the field operation.

The results of this repair operation remain uncertain as of this date. One or more of the formations above the alloy squeeze zone that show gas presence could be the source of the continuing SCVF. These zones may have been charged by gas from below during the operating period of the well, and their limited gas content may dissipate with time. We do not know the effect of the presence of heavy oil within the leak channel on the sealing ability of the alloy, though the high specific gravity alloy clearly displaced a substantial quantity of it.

d. ConocoPhillips Well 11-12-024-13W4

This well is in southern Alberta near the town of Cessford. It was drilled to a depth of 1035 mKB and completed in December 2000 by perforating 1002.0-1003.5 mKB of the Lower Mannville formation. In 2012, the well was plugged at 996 mKB and cement was dump bailed on top of the plug for abandonment.

Open hole logs on the well noted that gas sources were possible from coal seams that exist between 247 mKB and 305 mKB.

In July 2012, SCVF was noted, and the interval 973.0-975.0 mKB was perforated, acidized, and squeezed with cement based upon noise and temperature logging that indicated that the gas source was possibly below this depth. No effect on the SCVF was noted.

In March 2013, two intervals of 442-446 mKB and 368-372 mKB in the Milk River formation were perforated, acidized, and squeezed with cement. No effect on the SCVF was noted.

In October 2014, the client requested that Seal Well perform a bismuth alloy squeeze in the Milk River formation in the perforated interval 264.0-264.6 mKB. A Doull vent meter was installed on the well vent at surface, and it measured a gas leak rate of about 1.5 m^3/day. It was recognized that the Milk River is a sandstone formation, but one with poor permeability such that it was hoped that an annular plug within it would not be by-passed by the leaking gas.

The vent meter data showed that the perforation of the target interval had interdicted at least one leak channel. The alloy squeeze was performed, and the SCVF rate was stopped entirely for a period of about 36 hours. At that point, the pressure at the surface vent climbed once more, but to about half the previously measured values. The Milk River formation permeability was probably sufficient at the repair site to allow gas to by-pass the alloy plug that was otherwise successfully set. However, coal seams exist above the squeeze site and could be the source of the residual gas leakage.

Greenhouse Gas and Non-GHG Impacts

The direct GHG reduction benefits from the eight field tests reported here were measured and ranged between 200 and 600 T/yr CO_2e, depending upon the multiplier used to convert CH_4 reduction to CO_2e, either 25 as specified by CCEMC or 70 as the Intergovernmental Panel on Climate Change ("IPCC") has suggested[9]. The "before" and "after" GHG leak rates for the eight field test wells reported here are tabulated below:

Operator	Well	Leak Type	Leak Before Alloy Deployment m3/d	Leak After Deployment m3/d	GHG Reduction T/yr CO2e
Cenovus	16-08-006-13W2	SCVF	0.1	0	0.6
Cenovus	12-08-006-13W2	SCVF	0.1	0	0.6
Cenovus	08-03-006-14W2	SCVF	0.1	0	0.6
Cenovus	14-11-019-11W4	Casing Plug	10.0	0	57.3
Cenovus	16-02-016-15W4	Casing Plug	10.0	0	57.3
Cenovus	08-26-019-12W4	Casing Plug	10.0	0	57.3
ConocoPhillips	14-29-046-5W5	SCVF	7.0	0	42.0
ConocoPhillips	11-12-024-13W4	SCVF	1.5	0.5	3.0
	Totals		41.5	0.5	218.7

The source of CH_4 leakage can be from three well conditions, surface casing vent flow ("SCVF"), gas migration outside surface casing, or from casing abandonments. SCVF is gas flow within the annulus of wells between the outside surface of casing and the wellbore wall. SCVF rates above 300 m^3/day are classified by the AER as “serious” and must be repaired immediately before a well can be operated. SCVF rates below 300 m^3/day are classified by the AER as “non-serious” and must be repaired before the well is abandoned.

Non-serious SCVF wells can leak for many years until they are finally repaired and abandoned, and, as has been pointed out earlier in this report, the repair of this type of leak with traditional methods has been historically difficult and very expensive. The number of wells in Alberta that exhibit SCVF and the average SCVF leak rate are not known with precision. The AER records show the number of such wells that are reported immediately after completion at about 22,000 presently. However, SCVF can develop well after completion and are not included in AER records. One authority estimates that 14% of western Canadian wells exhibit SCVF[9], and, since the number of wells presently existing in Alberta is about 430,000, the actual number of existing SCVF wells may be of the order of 60,000. If one assumes that the average non-serious SCVF leak rate is a modest 10 m^3/day, then the present SCVF contribution to Alberta’s GHG emissions is between 3.5 million and 10 million T/yr, again depending upon the multiplier used to convert CH_4 to CO_2e emissions.

The other source of potential GHG emissions is from wells that are abandoned using the plugging method presently approved under AER’s Directive 020. This method requires setting of a mechanical bridge plug within 15 meters of the top-most production interval and the addition of an 8 meter long cement column on top. As related earlier in this report, as of January 1, 2008, the cap added at the near surface must itself be vented to the atmosphere in order to prevent build-up of potentially dangerous accumulations of any CH_4 that leaks around the plugs below. The sealing element used in mechanical plugs is nitrile rubber which is likely to deteriorate over time in the casing environment. The 8 meter cement column is also likely to leak because of shrinkage or other factors. One authority has estimated the likely service life of the bridge plug/cement combination at from 5 to 30 years[18]. If we assume that the about 150,000 wells in Alberta that were abandoned before January 1, 2008 were sealed with a fully welded surface cap and do not ever leak, then the number of wells that will likely eventually leak if the present Alberta casing abandonment method remains in place is about 280,000 even if the roughly 10,000 wells added each year are ignored. If again one assumes that the average leak rate is a modest 10 m^3/day, then the future contribution to Alberta’s GHG emissions from this source is between 10 million and 30 million T/yr, without counting additional annual wells to the inventory and depending upon the multiplier used to convert CH_4 to CO_2e emissions. However, the actual future GHG emissions average could well turn out to be 10 or more times the estimate since the original production zones in these wells becomes in direct contact with surface vents when the mechanical bridge plugs fail.

When one considers the number of wells in Alberta that presently leak plus those that are likely to leak in future, there is a lot of work to do. The largest number of well abandonments conducted by a single operating company in a single year reported to this author is 1200. If the entire present inventory of leaking and potentially leaking wells is eliminated in ten years’ time, the rate of repair and remediation is 34,000 per year. Seal Well’s present capacity with its present equipment and staffing of one field unit and crew, and considering seasonal weather constraints, is between 50 and 100 wells per year. More equipment and people are obviously called for, which means more jobs in the oilfield service sector.

The table below illustrates an estimate of Seal Well’s existing annual capacity for well GHG leak repairs assuming no increase in equipment or personnel, and assuming an average well leak rate of 10 m^3/day CH_4 – a reasonable average leak rate for SCVF wells according to AER statistics. This well repair rate represents only about 2% of the rate required to repair all Alberta wells over a ten year period. The number of wells that can be repaired annually can be multiplied by the number of field units and crews available to carry out the work.

Year	Wells Repaired	Cumulative Wells Repaired	GHG Reduction T/Yr CO2e
2016	75	75	4275
2017	75	150	8595
2018	75	225	12,892
2019	75	300	17,190
2020	75	375	21,487
2021	75	450	25,762
2022	75	525	30,037
2023	75	600	34,312
2024	75	675	38,587
2025	75	750	42,862

Overall Conclusions

The use of the bismuth-tin eutectic alloy has been shown by the results obtained in Project C110113 as both a permanent sealant for abandonment plugging of wells and as a superior repair sealant for SCVF problems. The deployment procedures are relatively straight-forward and economical. For the sealing of wells penetrating a geological formation being injected with CO_2 for either sequestration or tertiary oil recovery operations, it is clearly superior to any other sealant presently available to the industry.

Scientific Achievements

In February 2014, Seal Well made a presentation before the monthly meeting of the Canadian Society for Gas Migration in Calgary. The Birss Group at the University of Calgary is planning a series of papers in scientific journals regarding the corrosion properties of the bismuth-tin eutectic alloy. Seal Well will be reviewing the work conducted to determine the feasibility of patent applications to add to Seal Well's patent portfolio obtained prior to the inception of Project C110113.

Next Steps

The challenge for developers of any new technology to establish it with the upstream oil and gas industry is substantial, especially when it does not pertain to revenue enhancement for operators. We have shown by field tests to date that our bismuth alloy squeezing procedures for SCVF repair are much less costly than the historical costs incurred by western Canadian operators using traditional procedures and sealants. Nevertheless, there is no substitute for additional field demonstrations to gain necessary credibility to persuade a conservative industry. We will continue marketing efforts to obtain field projects to the maximum extent of resources available.

We expect to be called upon to demonstrate our bismuth alloy well sealants during the course of CMC's Field Research Station directed by the Containment and Monitoring Institute. We have no details or timing regarding our participation at this time.

The use of the bismuth-tin eutectic alloy as a permanent sealant for abandoning wells in Alberta has been successfully demonstrated in Project C110113. Our procedure, however, is modestly more expensive than the abandonment procedure allowed by AER's Directive 020, and, therefore, the use of the alloy sealant is difficult to sell to a very cost-conscious industry even when its long term superiority is acknowledged. The AER has been very cooperative in granting special approval for the use of the alloy thus far for specific wells. Nevertheless, more is needed from AER to encourage the use of a better abandonment procedure for Alberta in order for the greatest GHG emissions benefit ultimately to be realized. North Sea standards quoted earlier are the most rigorous in the world for permanent well abandonment, and AER's present Directive 020 procedure does not comply with the NORSOK Standard in any respect.

Assuming the availability of increased resources, Seal Well's heating tools and control electronics could be dramatically improved. The existing equipment used in Project C110113 was adequate for the purpose, but also demonstrated certain shortcomings that would enhance the success of commercial development. We are exploring additional Alberta development programs to address this issue.

The sheer number of the GHG emission sites associated with oil and gas production in Alberta and elsewhere in Canada cries out for maximum dissemination of the bismuth alloy sealant technology to the existing oilfield service industry. Seal Well is willing to license its intellectual property to such companies under equitable terms and to teach our techniques to licensees to accelerate progress in reducing emissions.

Seal Well has received numerous inquiries regarding our bismuth alloy technology from and extended discussions with US and other international oilfield service firms, including one Norway-based firm that operates under NORSOK standards. The technology is applicable to the more complex well architectures used offshore, but deployment equipment enhancements are required to deal with the larger diameter tubulars involved.

Communications Plan

Seal Well will shortly overhaul its web site to include at least non-confidential aspects of Project C110113 results and conclusions. We will continue presentations to well operators and service firms to gain acceptance from the industry. These are typically oral presentations using PowerPoint slides wherein CCEMC's crucial support is fully acknowledged.

We believe that our active participation in the proceedings of the Canadian Society for Gas Migration ("CSGM") is particularly useful. The CSGM membership includes well operators, service companies, and regulators, all of whom joined together for and are interested in GHG emissions reduction through the development of more effective and economical well remediation and abandonment procedures.

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