SPE SPE-156962-PP

An Analysis of the Caprock Failure at Joslyn

M.R. (Mike) Carlson, RPS Energy Canada Ltd.

This paper was prepared for presentation at the SPE Heavy Oil Conference Canada held in Calgary, Alberta, Canada, 12–14 June 2012.

Abstract

A significant caprock failure occurred on the Joslyn SAGD property in 2006, which has had wide impact on the approval of future SAGD projects. Two reports were released by the Alberta Government: "Total E&P Canada Ltd., Surface Steam Release of May 18, 2006, Joslyn Creek SAGD Thermal Operation, ERCB Staff Review and Analysis, February 11th, 2010" and "Summary of Investigations into the Joslyn May 18th, 2006 Steam Release, Total E&P Canada Ltd.". The latter report is very large. A number of potential mechanisms are postulated without definitive resolution. The most likely failure suggested involved transmission of fluids up a 50,000 mD chimney and a pancake shaped lens of high pressure steam that resulted in a shear failure of the caprock.

The author believes that this scenario is unlikely from a geological and heat transfer perspective. There are other anomalies. Peak stresses in most caprock coupled reservoir-geomechanical simulations normally peak at 3 to 7 years after start-up. However, the Joslyn failure occurred immediately after conversion from partial SAGD to full SAGD, in which the producing well was killed and a PCP pump was run.

There are other issues that should be considered that include:

1. How hydraulic fractures are initiated and propagated. The literature shows us:
    a. computer design programs that predict fracture propagation and shape,
    b. analytical solutions that also show expected fracture morphology; and,
    c. physical examples which have been dug up or cored
2. In addition the geological record provides excellent analogue information on the morphology of high pressure intrusions. These various types of data will be compared to the observed morphology derived from the 3D seismic.

Earlier work by Edmunds and Good has shown that extremely transient conditions exist in SAGD wells that result in “geysering” or slugging within the producing well. The energy available from water and steam is enormous. The nuclear and power industry previously made these similar discoveries after a series of catastrophic failures of piping systems. Analytical and computer simulation tools from the nuclear industry will be used to show that extremely high pressure transients, many times over fracture initiation pressures, can be expected. This is the same mechanism that resulted in the catastrophic failure of MEG Energy’s Christina Lake main steam distribution line.

In summary, there is every reason to believe that when hot steam was injected into a cooled (water) condensate filled well; very large pressure transients can be expected from phase changes within the piping that should result in a frac to surface.

Introduction

Remarkably little has been written about the Joslyn failure. At present, there are no technical papers on the failure. Papers that deal with related topics include:

1. Some oblique reference to the matter in "Effective Caprock Determination for SAGD Projects" by Collins, Walters, Perkins, Kuhach and Veith[1]. The substantive subject matter is steam rises that could be expected. The authors are attempting to infer steam rise for the Tamarack project proposed by Ivanhoe Energy.
2. There is indirect discussion in "Geomechanical Simulation of Caprock Performance for a Proposed, Low Pressure, Steam Assisted Gravity Drainage Project", by Uweira-Gartner, Carlson, Walters and Palmgren[2,3]. This project is at a similar depth, and the modelling result will naturally draw comparison with the Joslyn project. The main topic the development of Alberta Oil Sands Clearwater West commerical pilot.
3. A presentation was made at the 2011 CSPG / CSEG / CWLS convention "Joslyn Creek SAGD: Geologic Factors Related to a Surface Steam Release Incident, Athabasca Oil Sands Area", by Hein, and Fairgrieve[4]. The geological conferences do not have formal proceedings and papers. The presentation has been available on line as a pdf download of a Powerpoint presentation. The material in this paper is very helpful.
4. There is information on caprock integrity in the WHOC-609, "Caprock Integrity Analysis in Thermal Operations: An integrated Geomechanics Approach" by Khan, Han, Vishteh and Khosravi[5]. This paper is after the Joslyn failure, however, there is no discussion of Joslyn in the paper.

In summary, there is virtually nothing from an engineering perspective on the caprock failure at Joslyn the peer reviewed technical literature.

Public Domain Reports

Two reports are available from the Alberta Government: "Total E&P Canada Ltd., Surface Steam Release of May 18, 2006, Joslyn Creek SAGD Thermal Operation, ERCB Staff Review and Analysis, February 11th, 2010"[6] and "Summary of Investigations into the Joslyn May 18th, 2006 Steam Release, Total E&P Canada Ltd."[7]. The latter report is very large at over 1,000 pages. The latter part of the Total report is a large section of backup enviromental data. None-the-less the report is of a substantial size. As may be deduced from the above, these reports have not been summarized for inclusion in the technical literature. For those involved in the design and implementation of SAGD projects, these reports should be studied in detail.

Key Conclusions

The two reports provide different interpretations of the causes of failure. Excerpts from these reports are provided as follows (paraphrased from the ERCB report). Total's views were:

1. *A fast, gravity-driven local developoment of a steam chamber or "chimney" to the top of the SAGD pay zone, probably involving sand dilation. This occurred over a 4-month period while well pair 204-I1P1 was on steam circulation. (Total used high density three-dimensional [3-D] seismic, analystical work, dilation theory, and simple reservoir simulation to support this.)*
2. *A lateral extension of the presssurized area below the first major shale barrier in the Upper McMurray. (Total used 3-D seismic, geology, and simple geomechanical modelling to support this.)*
3. *One or more shear failures on the edge of this pressurized areas that allowed the steam to breach within a gas zone in the Upper McMurray and/or Wabiskaw C sand or in the Wabiskaw A water sand under the Clearwater caprock. (Total used simple geomechanical modelling and historical pressures and steam rates to support this.)*
4. *Significant water and steam storage in the localized SAGD chamber, fracture system and Wabiskaw and Upper McMurray porous and permeable sands. (Total used historical steam rates and presssures, geology, simple geomechanical modelling, and the explosive nature of the steam release to support this.)*
5. *A catastrophic shear failure of the Clearwater caprock, leading to release of steam at surface on May 18, 2006. (Total used simple geomechanical modelling to support this.)*

Total (2007) also investigated other possible failure mechanisms:

1. *steam moved up nearby vertical wellbores with poor cement bonds.*
2. *steam moved up through natural fractures within the reservoir and caprock, and*
3. *high pressure steam injection induced vertical fracturing of the reservoir and caprock.*

Total concluded that none of these alternative scenarios was likely and provided arguments against each one.

The ERCB (2010) agreed with some, but not all of, Total's (2007) interpretations. The following was reported by the ERCB:

Staff reviewed Total's most likely steam relaease scenario and the three alternative scenarios, as summarized below:
Total's Most Likely Scenario

1. *Staff agrees that the mini-frac test result indicates that only horizontal fracturing of the reservoir and caprock would occur at Joslyn Creek. However, staff believes that the test results may not be representative.*
2. *Staff believes it is unlikely that a dilation chimney would develop during the 4-month circulation period of well pair 204-I1P1 and provided arguments to support this view.*
3. *Staff agrees with Total's high density 3-D siesmic interpretation that the adjacent vertical wells were not within the narrow disturbed zone that extended down to the injector 204-I1. However, the vertical wells were within 20 m of the injector 204-I1 and staff has concerns with the the accuracy of seismic over such short distances.*
4. *Staff agrees with Total that the explosive nature of the steam release required storage of the steam and hot water below the caprock. Therefore the steam release did not likely occur as a single fracturing event form the wellbore to surface on May 18, 2006. This is supported by pressure and injection data that indicate an initial fracturing event on April 12, 2006.*
5. *Staff believes that Total's geomechanical modelling was reasonable and showed that shear failure of the caprock could have occurred due to pooling of high pressure steam and water in porous and permeable zones beneath the Clearwater shale.*

In addition, the ERCB (2010) also reported other alternative scenarios for steam release:

1. *Staff believes that the most likely initial pathways for steam rise were either a vertical fracture or horizontal fracture that propagated to a nearby abandoned vertical evaluation well and then moved up through gaps in the cement plug. Arguments were provided to support this view.*
2. *Staff agrees with Total that the vertically rising steam established communication with an Upper McMurray/Wabiskaw C gas zone or the Wabiskaw A sand at the base of the Clearwater caprock and that steam and water pooled in one or more of these porous and permeable intervals.*
3. *Staff believes that it is likely that the large pool of high-pressure steam and water eventually led to shear failure of the caprock.*
4. *Staff believes that natural fractures and the presence of silty, sandy intervals in the caprock could have contributed to the steam release.*

The interpretations and conclusions presented indicate the cause of the Joslyn failure was not definitiveley concluded.

Hydraulic Fracture

The government has concluded that the fracture pressure at the horizontal injector was exceeded at 1800 kPa and that a fracture was propagated either horizontally or vertically. The author believes this is a reasonable conclusion.

Conclusion number 1 also states that the fracture propagated up a nearby abandoned well. It would also be helpful to know if the fracture was vertical or horizontal. A horizontal fracture suggests that fluid would be distributed in a horizontal fracture, which should distribute steam distribution and not concentrate it. The logical solution at this step is to examine the morphology of the failure.

Shape of Disturbance

Ordinarily if we were to examine a pipeline failure we would look at the metal where the pipline failed and looked for characteristic patterns on the metal that would indicate the cause of failure. In the matter at hand there is a detailed geophysical description. The following is highlighted – looking across the wellpairs:

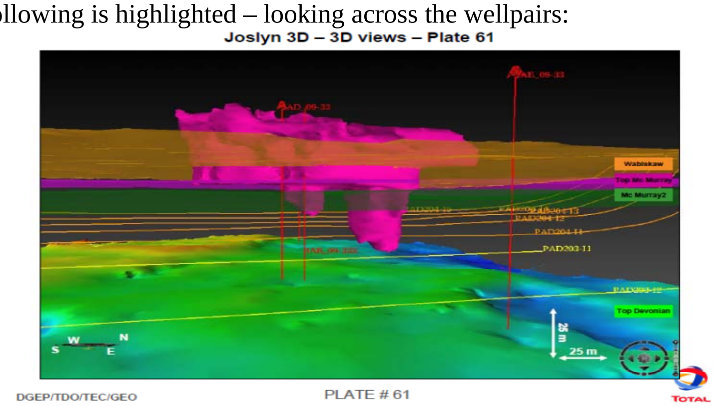

Figure-1 Joslyn Seismic 3D view from side

Looking down the wellpairs:

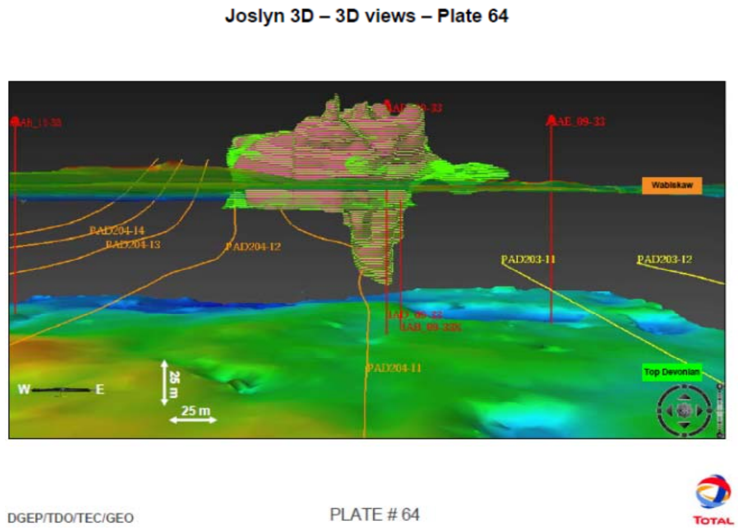

Figure-2 Joslyn Seismic 3D view down axis of wells

Looking from below:

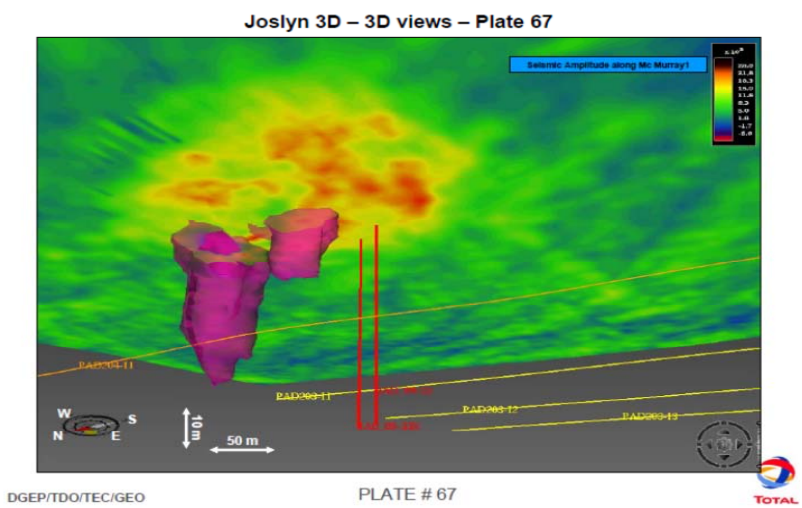

Figure-3 Joslyn Seismic 3D view from underneath

The picture from below would seem to indicate the existing vertical strat wells were not involved in the failure. More detail is provided in a cross-section. It is suggested in Total's report that the fluid leakoff occurred in stages:

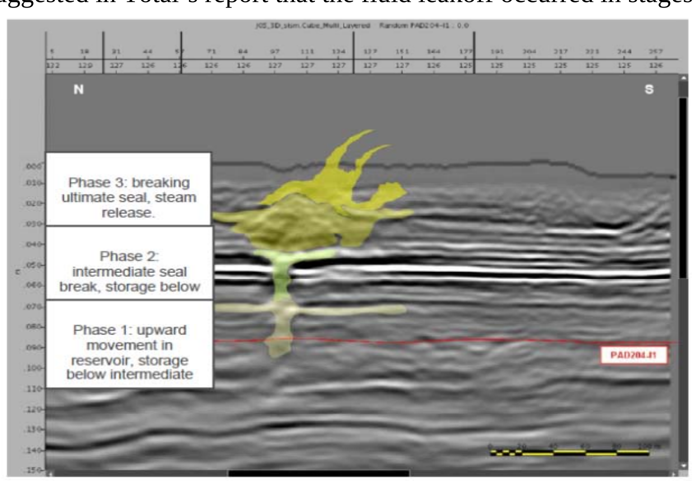

Figure 30 : Walking through the steam release on seismic – Phase 3. This phase corresponds to the ultimate step before and during the catastrophic steam release at surface.

Figure-4 Joslyn Seismic Corss Section Showing Pipe

The different phases are depicted in slightly different colours. The shape of this does not correspond to a simple vertical fracture or for that matter a simple horizontal fracture. It is also clear that there is some vertical feature. The features cuts across bedding planes that are quite well defined and suggests that whatever has caused the disturbance was most likely not stratigraphic. If a channel were to exist, its continuation would be visible elsewhere in seismic. The lateral distribution of disturbance, which indicates fluid movement, would have to be at high pressure to produce a leak-off pattern.

Fracture Shape Expected

The seismic disturbances are not simple. Normally fractures are vertical because the horizontal stresses are lower than vertical stresses. A vertical "penny" shaped frac is generated. Continuing the analysis, If the wells are at approximately 100 meters, then the overburden stress is 100 * 2.1 * 9.8 ~ 2058 kPa (about 20.6 kPa/meter). The vertical and horizontal stresses are actually fairly close. The presence of the wellbore will also disturb the stress field and this will affect the inititial propagation. The orientation of the fracture will therefore not be obvious.

Fractures can be initiated horizontally or vertically, and much is known about its propagation direction based on geology, surface observations, core holes, mathematical analysis, and numerical modelling. Starting with geology we can see direction changes in naturally occurring dykes and sill. The following diagram was derived from an outcrop study in South Africa[8]. We can see clearly that the lower portion the hot rocks are moving upward vertically. They then branch out somewhat like a flower bunch. The diagram below is 2D and we must extrapoloate this to 3D. No information is given on the vertical section, however, we may infer that is either vertical like a pipe, or perhaps a planar feature.

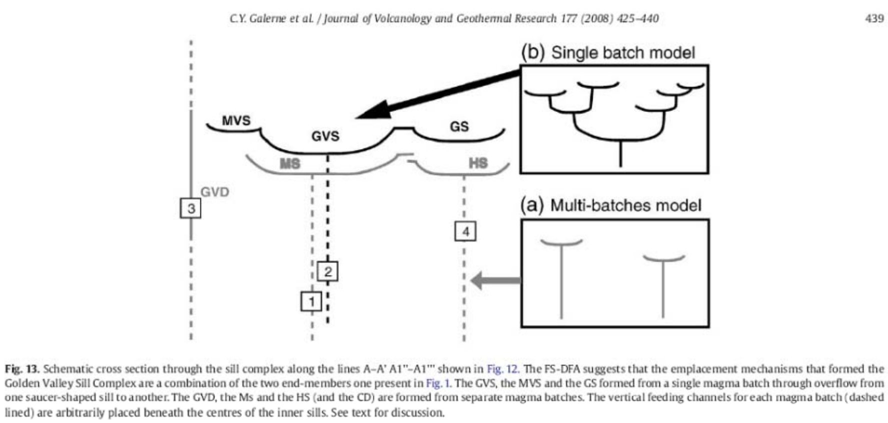

Figure-5 Branching of Dykes and Sill in South Africa

The spreading nature of the natural sills and dykes is manifested in the upper sections of Figure-1 through 4.

It is possible to model fractures with finite elment programs. The folliwng shows the fracture trajectories from computer simulations utilizing the FRANC2D code, developed by the Cornell Fracture Group (2010) for an element of symmetry, which is a 2D representation of a 3D feature[9]:

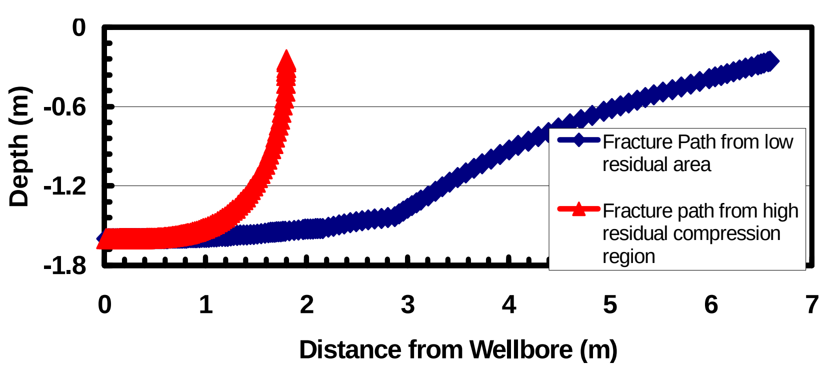

Figure 6 FRACANAL Fracture Shapes – Horizontal Frac

A fracture that starts horizontally turns vertical either as a saucer (plate) or cup, depending on the amount of horizontal stress. This is an elment of symmetry and it would be expected that the fracture generated would be similar to a cup. If the horizontal principal stresses are different, the shape of the cup will be somewhat elliptical. From the above, the cup would eventually be expected to branch. This has been confirmed in situ within the Athabasca oilsands[10].

This type of fracture morphology is indeed seen in the 3D seismic depictions. However, Figure-4 shows that some significant dilation has taken place and this suggests some additional mechanism, either from the fracture directly or as a result of leak off from the fracture. The dilation chimney looks like what is known as a pipe in soil mechanics and represents a special stress condition.

Effective Stress

A key concept from soil and rock mechanics is effective stress. The concept is shown in the diagram below in which soil (and rocks – which are viewed as cemented granular materials) that have pores spaces filled with water:

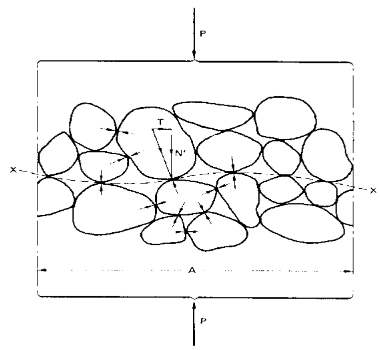

Figure 3.1 Interpretation of effective stress.

Figure-6 Explanation of Effective Stress Concept

From the above a force balance can be done on the dashed line X-X. In equation format, the total stress applied is equal to the fluid pressure plus the stress carried by the grain structure:

$$\sigma = \sigma' + u$$

where , σ = applied stress
σ' = effective stress
u = pore pressure

Or, reordering the equation, to solve for the stress carried by the grain structure (effective stress σ')

$$\sigma' = \sigma - u$$

If the fluid pressure exceeds the applied load there will be no net grain to grain force and the sand particles can (and will) disaggregate. This is a zero effective stress.

Whatever has caused this disturbance must be at a sufficiently high pressure to cause extreme disruption to the fabric of the rock and high enough to cause some leakoff into the existing strata. This suggests very high pressures, well above ISIP's from a mini-frac test.

Gas Pipes

There are modern examples of such distrurbances that are on seismic and have also been observed in Pli-Pleistocene clay in Cap Vagia on the Greek island of Rhodes. A seismic representation from Nigeria is shown below[11]:

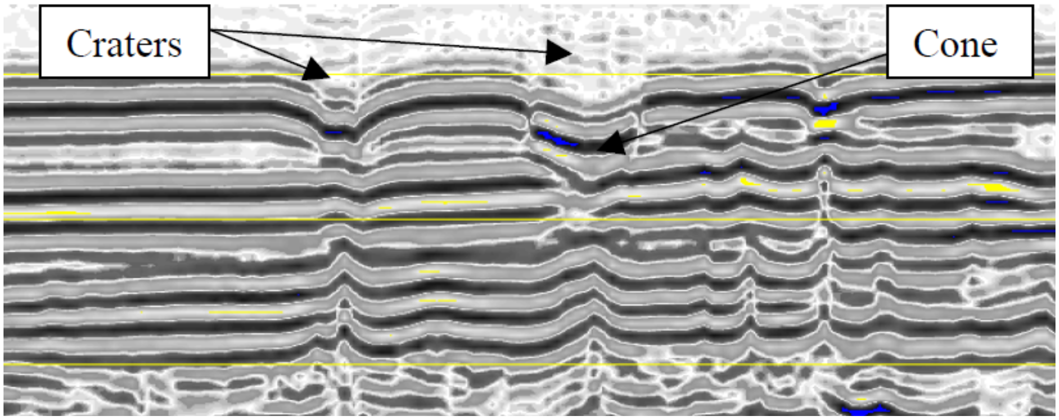

Figure-7 Seismic Picture of Gas Pipe in Nigeria

The structures found in Rhodes show vertically fractured pipes in poorly consolidated (can-be-cut-by-knife) argillaceous cap rocks. Natural processes do create vertical permeable zones in cap rocks and that they can be formed in relatively loosely consolidated cohesive claystones. This corresponds to high pressure fluids migrating upwards. A classic pipe caused by zero effective stresses. The above closely resembles the picture in Figure-4.

Fracture Pressure

While the frac pressure is reasonable, the fracture pressure was only slightly exceeded. It is unlikely that this would actually propagate a fracture. This is well established technology. Suppose we started out with the deliberate intent to frac a horizontal SAGD producer. What would we have to do? We know from mini-fracs and similar analysis that a fracture pressure history looks something like the extract taken from the AOSTRA Mini-Frac Manual:

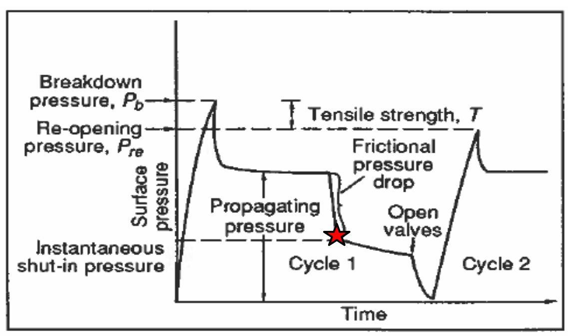

Figure 2–2. *Schematic representation of the stages in the growth of a mini-frac (from Roegiers, 1989).*

Figure-8 Fracturing Pressure Expectations

No fracture will be propagated if just the ISIP is reached (shown with a red star in the above). For the fracture to propagate additional pressure is required to overcome friction in the fracture, create a stress concentration at the tip and more yet to overcome tensile strength and actually initiate the fracture. From the diagram above, one must get to Pb, breakdown pressure. This is considerably above the ISIP. In practice, a 10 percent factor of safety, which is the historical norm for fracture pressure safety factors, actually has a huge margin of inherent safety.

All of the above features require pressures that are well above fracture pressures.

Thermalhydraulics

Recently there have been a number of explosions of surface steam lines. This is the result of condensation induced water hammer. The ERCB has investigated this matter and produced report “MEG Energy Corp. Steam Pipeline Failure, License No. P 46441, Line No. 001, May 5th, 2007”, ERCB Investigation Report, September 2nd, 2008[12]. The following has been paraphrased from the report:

At about 5:33 a.m. on Tuesday, May 5, 2007, MEG Energy Corp. (MEG) became aware of a potential

> *release situation at its Christina Lake Regional Project when the control room operator noted an "electrical blip and a muffled pop sound." Communication was lost between the Digital Control System (DCS) and Pad A (location of six horizontal well pairs) and a large plume of steam was observed rising in the direction of Pad A. … MEG staff responded in the direction of the steam plume to confirm the location of the release but were stopped about half way to Pad A by sections of the aboveground 24-inch (610 millimetres [mm]) steam pipeline and downed power lines lying across the road.*

Fortunately there was no one near the facility when it failed and there were no injuries. The mechanism of failure was explained by the ERCB as follows:

> *A condensation induced steam hammer is sometimes called a condensation induced water hammer* ***(CIWH)*** *or a steam bubble collapse and is a rapid condensation event. It occurs when a steam pocket becomes totally entrapped in subcooled condensate. As the steam gives up its heat to the subcooled condensate and pipe walls, the steam changes from a vapour to a liquid. The continued loss of steam by this phase transformation induces fresh steam to flow into the steam pocket in order to replace the lost steam. Steam flow over condensate will tend to draw up waves in the condensate via the Bernoulli Effect. If the rate of heat transfer is rapid enough for a given condensate level, the induced steam velocity will draw up a wave high enough to seal the pipe. This is critical because the wave seal effectively isolates the steam pocket from the upstream supply of steam. At that instant, ongoing condensation causes the vapour void to collapse because the volume of liquid is about 100 to 1000 times smaller than the precursor volume of steam. The associated drop in pressure within this void acts like a vacuum that causes the condensate waves to crash into each other. There are also rebounding shockwaves (see Figure 1).*

This is shown diagrammatically as follows:

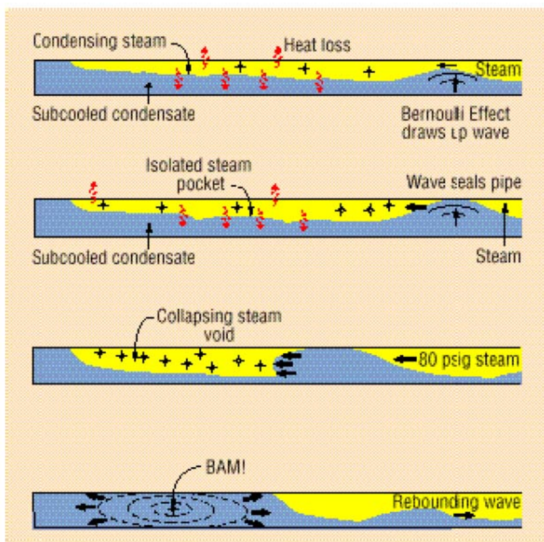

Figure 1. Condensation induced water hammer

Figure-9 ERCB Explanaton of Condensation Induced Water Hammer (CIWH)

In simplified terms, if steam injected into a line with cold water (condensate) can create a pressure wave large enough to burst line pipe, then the fracture pressure could be exceeded by over an order of magnitude (10 times). Since the liners are slotted, limited to no pressure drop would be expected between the wellbore and the formation.

The author has obtained computer modeling on the potential for condensation induced water hammer within a Steam Assisted Gravity Drainage Well from thermal hydraulics experts: Atomic Energy of Canada Limited. The preliminary study modeled a very simple event – a valve closure, the results are shown below:

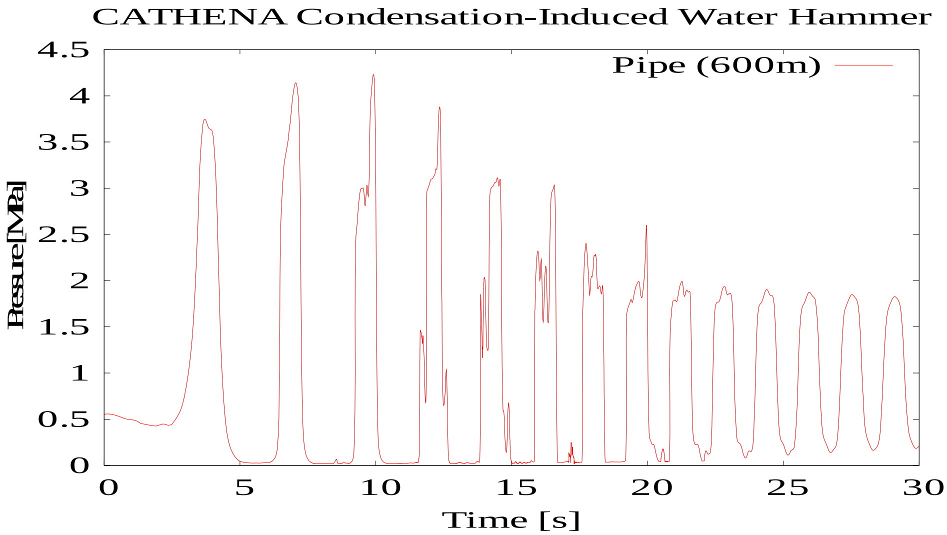

Figure-10 Void Collapse Model in SAGD Wellbore

The work was completed by Atomic Energy Canada Limited, a federal government national laboratory that has been responsible for the development of Canada`s nuclear program. The explanation provided by AECL is as follows:

Water hammer is defined as the change in pressure that occurs in a fluid system as a result of a change in the fluid velocity. This pressure change is a result of the conversion of kinetic energy into pressure, which creates compression waves, or the conversion of pressure into kinetic energy, which creates rarefaction waves. In general, decreases in pressure as a result of water hammer are not a concern in thick walled piping built to withstand high pressure, since these pipes can withstand any under-pressures caused by this phenomenon. On the other hand, water hammer induced compression waves represent a potential threat to piping and component integrity and thus represent an important safety concern.

Water hammer can be classified into two different groups: single-phase water hammer and two-phase water hammer. In single-phase water hammer, the water is initially in the liquid state, and remains in the liquid state for the duration of the water hammer event. Two-phase water hammer can be classified into three different general categories:

1. *Two-component/two-phase water hammer, which involves both water and noncondensables,*
2. *One-component/two-phase water hammer involving water and void created by column separation or cavitation, or in which the gas and liquid phases are at the same temperature, commonly known as void collapse water hammer, and*
3. *One-component/two-phase water hammer in which there is significant heat and mass transfer between phases, commonly known as condensation-induced water hammer.*

In the first two categories the gas and liquid components are at the same or nearly the same temperature and the water hammer phenomena are driven primarily by momentum considerations. In the third category, the water hammer phenomenon is driven by thermodynamic considerations in which high temperature steam is condensed by subcooled water. The investigation of two-phase water hammer is of particular importance since it represents the potentially most destructive form of water hammer.

Condensation induced water hammer has caused many explosions and is a significant cause of fatalities in the power and boiler industry. Steam lines must, by code, have ``steam traps`` to drain condensate from steam lines. Steam traps and condensation induced water hammer must be considered in SAGD injector design. To date, horizontal wells have not had stream traps installed.

The diagram shows that valve closure causes extreme pressure spikes that are over 3 times the operating pressure. For a 1,000 kPa operating pressure in a SAGD wellbore, this means transients can be expected as high as 4,000 kPa. This is considerably over the fracture pressure of 1800 kPa. Over time, a fractured and dilated zone would propagate vertically.

Modelling of an injection well using WAHA

Modelling has also been carried out using WAHA[13,14,15] for an injection well utilizing an injection rate of 80 tonnes of steam a day with a 25˚ C temperature differential. The results are shown below. The wellbore has been simplified – only the horizontal section has been modelled. The liner has been simplified in that all of the fluid exits at the end of the well, where in reality there would be a distributed leakoff into the formation. The pressures are shown 75 meters from the heel of the well. The input to the model (such as heat transfer coefficients) was not tuned and only the first minute is shown. The blue line represents the pressure and shows short term transients of over 4,000 kPa. The well trajectory has been changed for the purple trace, with the objective of preventing CIWH. It is possible, with proper design, to eliminate these spikes. The red line represents the maximum pressure in the well. Above this pressure the formation will hydraulically fracture.

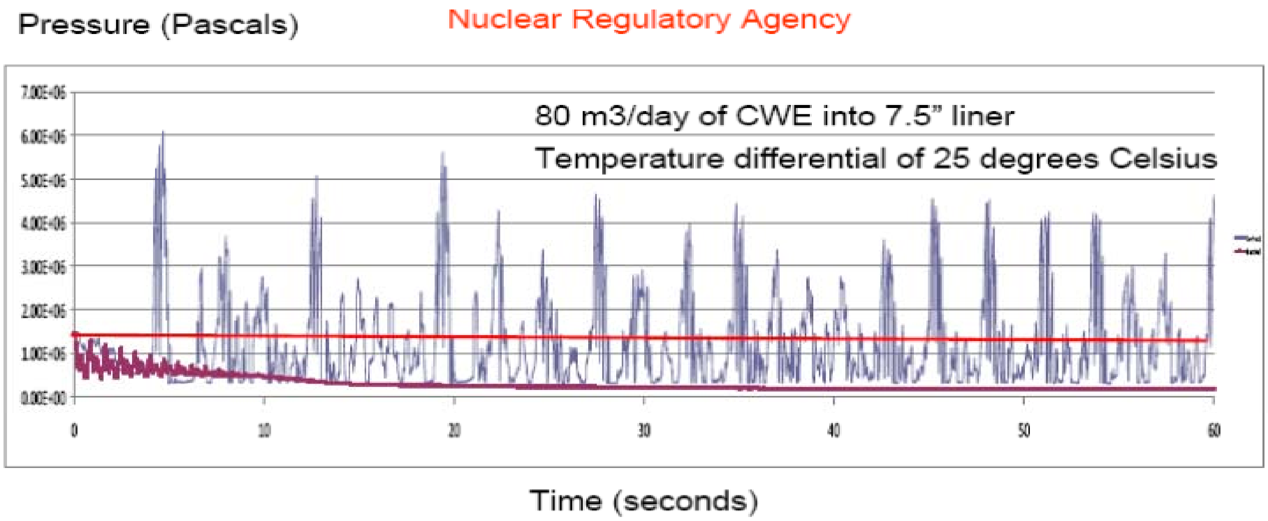

Figure-11 WAHA simulation of injection well – for first 60 seconds

It is also possible to build some fairly simple physical micro-models using some vinyl tubing and a wall paper steamer. All of which can be purchased at a local building store for a nominal cost. With a bit of epoxy putty, the tubular arrangements found in SAGD wells can be cheaply constructed. This demonstrates that the geometry definitely exists for water hammer. The latter experiments are, of course, at a very low pressure, approximately 4 kPag. The author believes that CIWH is not intuitively obvious and this visualization is critical.

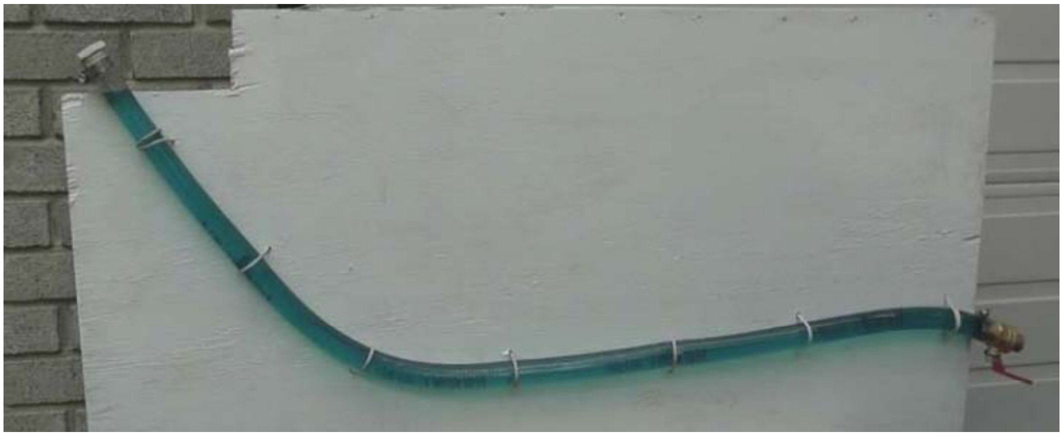
Figure-12 Physical model of water hammer in a SAGD injector

Surface Damping

Because the riser section is typically gas (steam) filled, there is a large gas cushion effect and the downhole pressures do not manifest at surface. For instance, in the demonstration model shown in Figure-12, the wallpaper steamer operates continuously despite the downhole water hammers.

For most SAGD projects steam injection pressures are measured using a bubble tube. This is a very simple device that consists of a 0.25″ diameter steel tube with a one way valve on the bottom. Nitrogen is injected at surface and the pressure in the bubble tube is recorded. The high transients from a CIWH cause the bubble tube valve to slam shut, so the pressures are not transferred to surface or to the recorder. Nitrogen continues to flow since it is compressible and when the short transient passes, the valve re-opens downhole with continued nitrogen flow at background pressures. There is therefore no surface expression of the pressure transient.

Observed Data

Observed data does exist, which has an appearance similar to that shown below. This data is problematical. The pressure sensors utilized were not sized to go to the pressure spike levels that occurred. The spikes are also very short, as shown by the modelling, and most pressure sensors are designed for long term averages. Note that both high pressures and void (zero) pressures are shown.

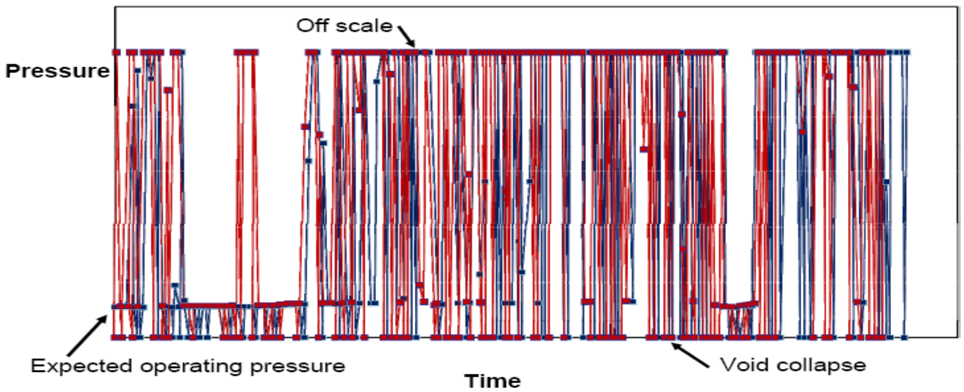

Figure-13 Cartoon of well pressure data. Red data is from heel, blue data is from toe

While conclusive proof is hard to draw from such data, the results obtained are not consistent with expectations. The data indicates pressure spikes more than sufficient to induce a hydraulic fracture. These events would logically involve relatively small volumes of fluid since the spikes are so short. It is clear that the process is repetitive.

The average operating pressure is also a factor. The hydraulic fractures will heal with a return of cold fluids into the wellbore. This will tend to perpetuate the process. If the operating pressure is close to fracture pressure, the fracs will not heal and will steadily progress – a frac by a “thousand cuts”. Failure would therefore not be instantaneous.

Summary of Proposed Mechanism

Based on an examination of the morphology of the failure that occurred at Joslyn it is clear that high pressure caused a vertical propagation of a fracture / dilation chimney. Both Total and the ERCB have agreed that bottom hole pressures were measured and calculated to be in the range of 1800 kPa. This is not sufficient to produce this kind of morphology. Recent catastrophic failures of surface lines confirm that steam filled lines in contact with cold condensate are capable of independently generating very high pressures. Computer modeling of pipeline systems confirm that these conditions exist in SAGD wellbores. While not verified by subsurface recorders, there is clearly unexpected disturbances that are consistent with CIWH. Repetitive high pressure spikes would reasonably create a complex pattern of fractures and dilation that would propagate to surface. Such a mechanism could possibly exist in many different projects.

Conclusion

The Joslyn failure is a significant catastrophic failure affecting SAGD developments. Future licensing of SAGD projects will be uncertain if the cause of failure is not known with certainty.

1. The existing reports prepared by the Government of Alberta and Total did not conclusively identify the underlying cause of failure.
2. The geophysical interpretation provided by Total indicates that there is a characteristic shape to the failure that indicates a mixture of piping and fracturing occurred. This requires very high pressures.
3. The morphology observed is similar to that seen in the subsurface from fracs in groundwater remediation, dykes and sills, as well as gas pipes in a variety of settings.
4. If propagation of a fracture should start horizontally, it will rapidly change direction to represent a saucer and/or a cup shape. This has been verified in shallow groundwater remediation, geophysics and outcrop geology, as well as

from wells in the oil sands. This matches the shapes observed in Total's geophysics.
5. It is clear that dilation exists in the structure shown in Total's review of the failure. This would be consistent with pressures in excess of overburden load and zero (or negative) effective stresses.
6. Gas when it migrates in nature from deep in the earth creates pipe like structures with fractures.
7. It is unlikely that operating the well just over the calculated frac pressure would result in a fracture to surface. Propagating a fracture requires overcoming leakoff, friction pressure as well as the energy to disturb the formation.
8. Condensation water induced hammer has destroyed many surface pipelines and is a known source of very high pressures causing failures. The formation in a SAGD well is unprotected because the liners are slotted.
9. Computer simulations of SAGD wells indicate pressure spikes are likely and should be included in SAGD well design. The failure mechanism postulated fits well with the observed failure morphology.
10. Resolving the failure that occurred in Joslyn is critical for safely licensing future projects. Currently there are a number of shallow resources, including the Joslyn property, where significant reserves will be sterilized if safe operation cannot be reasonably assured.

Condensation induced water hammer has caused many explosions and is a significant cause of fatalities in the power and boiler industry. Steam lines must, by code, have ``steam traps`` to drain condensate from steam lines. Such failures have already occurred on more than one occasion in the oil sands. Steam traps and condensation induced water hammer must be considered in SAGD injector and producer design. While both Total and the ERCB have expended considerable effort and resources in evaluating the failure at Joslyn, the author believes other mechanisms should be considered.

References

1. Collins, Walters, Perkins, Kuhach and Veith; "Effective Caprock Determination for SAGD Projects", CSUG/SPE 149226, Canadian Unconventional Resources Conference held in Calgary, Alberta, Canada, 15–17 November 2011.
2. Uweira-Gartner, Carlson, Walters and Palmgren; "Geomechanical Simulation of Caprock Performance for a Proposed, Low Pressure, Steam Assisted Gravity Drainage Project", CSUG/SPE 148886; Canadian Unconventional Resources Conference held in Calgary, Alberta, Canada, 15–17 November 2011.
3. Uwiera-Gartner, M.M.E., Carlson, M. R., and Palmgren, C.T.S.; "Evaluation of the Clearwater Formation caprock for a proposed, low pressure, steam-assisted gravity-drainage pilot project in Northeast Alberta", SPE SPE-156962-PP, SPE Annual Technical Conference and Exhibition held in Denver, Colorado, USA, 30 October–2 November, 2011.
4. Hein, and Fairgrieve; "Joslyn Creek SAGD: Geologic Factors Related to a Surface Steam Release Incident, Athabasca Oil Sands Area", 2011 CSPG / CSEG / CWLS convention.
5. Khan, Han, Vishteh and Khosravi, WHOC-609, "Caprock Integrity Analysis in Thermal Operations: An integrated Geomechanics Approach", Proceedings for the 2011 World Heavy Oil Congress [WHOC11].
6. Total E&P Canada Ltd., Surface Steam Release of May 18th, 2006, Joslyn Creek SAGD Thermal Operation, ERCB Staff Review and Analysis, February 11th, 2010.
7. Total Canada, Summary of investigations into the Joslyn May 18th, 2006 Steam Release, TEPC/GSR/2007.006, December 2007.
8. Gelerne, C.Y., Neumann, E-R, Planke, S.; "Emplacement mechanisms of sill complexes: Information from the geochemical architecture of the Golden Valley Sill Complex, South Africa, Journal of Volcanology and Geothermal Research, Elsevier, 2008
9. Murdoch, L.C., Richardson, J.R., Tan, Qingfeng, Malin, S., Fairbanks, C, "Forms and sand transport in shallow hydraulic fractures in residual soil", Canadian Geotechnical Journal, 43: 1061-1073 (2006).
10. Chhina, H.S., Luhning, R.W., Bilak, R.A. and Best, D.A., "A horizontal fracture test in the Athabasca Oil Sands", CIM Paper No. 87-38-55, Preprint, Annual Technical Meeting of the CIM, June 7-10, 1987.
11. H. Loseth, L. Wensaas, B. Arntsen, N. Hanken, C. Basire and K. Graue, "11000 m long gas blow-out pipes", P524 EAGE 63rd Conference & Technical Exhibition — Amsterdam, The Netherlands, 11 - 15 June 2001
12. ERCB Investigation Report, MEG Energy Corp. Steam Pipeline Failure, License No. P 46441, Line No. 001, May 5th, 2007", September 2nd, 2008.
13. Gale, J., Tiselj, I., "Water hammer in elastic pipes", International Conference, Nuclear Energy for New Europe, Kranjska Gora, Slovenia, Sept. 9-12, 2002.
14. Giot, Prof. Michel, "Two-Phase flow water hammer transients and induced loads on materials and structures of nuclear power plants (WAHAloads)", European Consortium, UCL/TERM Batiment Simon Stevin, 2, Place du Levant, B-1348, Louvain-la-Neuve, Belgique
15. Progress Report on Research Activities in 2003, KFKI Atomic Energy Research Institute, Budapest 114, POB 49, H-1525 Hungary.

Additional Information

16. NUREG/CR-6519: Screening Reactor Steam/Water Piping Systems for Water Hammer, P. Griffiths, MIT, Sept. 1997.
17. Bjorge, R.W., Initiation of Water Hammer in Horizontal or Nearly-horizontal Pipes Containing Steam and Subcooled Water, Ph.D. Dissertation, MIT, January 1983.
18. M. R. (Mike) Carlson , "And now for something completely different: condensation induced water hammer and steam assisted gravity drainage in the Athabasca oil sands", NURETH14-600, The 14th International Topical Meeting on Nuclear Reactor Thermalhydraulics, NURETH-14 Toronto, Ontario, Canada, September 25-30, 2011 – peer reviewed and accepted for publication.
19. M.R. (Mike) Carlson, "Detailed Consideration of the Proposed Joslyn Failure Mechanism", in press CETI, April-May 2012.
20. M.R. (Mike) Carlson, "A discussion about condensation induced water hammer and caprock integrity"; Society of Petroleum Engineers, Edmonton Section, Dinner presentation, January 10th, 2012.
21. Carlson, M.R., "What every SAGD operator and engineer should know about potential failure by condensation-induced water hammer", Journal of Canadian Heavy Oil Association, September 2010.
22. Edmunds, N.R. and Good, W.K.; "The nature and control of geyser phenomena in thermal production risers", JCPT 96-04-04, April 1996, Volume 34 No. 4.