ACID GAS ACCIDENTAL RELEASE
WELL CONTROL

PREPARED FOR:

BC Oil and Gas Research and Innovation Society (BCOGRIS)

July 2019

Prepared by:

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July 30, 2019

Letter of Transmittal

BC OIL AND GAS RESEARCH AND INNOVATION SOCIETY (BC OGRIS)
PO BOX 9331 Stn Prov Govt
Victoria BC
V8W 9N3

Attention: Mr. Ken Paulson, P. Eng. - Fund Manager

Re: ACID GAS ACCIDENTAL RELEASE CONTROL METHODS
RECIPIENT AGREEMENT ES-WELL-2019-02

Attached please find the report on the thermodynamic behaviour and HS&E risks of an uncontrolled release of acid gas, as well as conceptual thoughts on potential blowout recovery methods for further investigation.

If you have any questions or concerns, please do not hesitate to contact me via email at Ray.Mireault.PEng@gmail.com or at (403) 829-3381.

Sincerely,

Ray Mireault, P.Eng.
Senior Engineer, Technical Specialist

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INTRODUCTION

Acid gas disposal involves injection of liquefied waste products, H_2S and CO_2, into deep underground storage reservoirs. An uncontrolled release of these wastes, due for example to a loss of well control, is unlikely due to existing industry safety systems, procedures and regulatory oversight. However, due to the high toxicity, low flammability and non-buoyancy of these waste products, potential health, safety and environmental (HS&E) consequences are unique and conventional methods to safely regain well control for natural gas releases may not be effective or safe should a sustained uncontrolled release occur.

In BC, there are currently 7 active acid gas disposal wells, 5 suspended and 4 abandoned. As the Province continues to develop its unconventional gas resources, retires and/or retrofits aging sour gas processing plants, and potentially implements carbon capture and sequestration (CCS) technology, the number of acid gas disposal wells may increase; concurrently increasing the number of industry personnel involved and potential for incidents. Effective regulation and management of these wells is best supported by comprehensive safety systems, personnel trained for the specific operations and the development of science-based procedures for safe mitigation of loss of well control incidents should they occur. Historically, well drilling and workovers present a statistically elevated risk of a loss of control events compared to other well operations.

Collaboration with international acid gas processing experts, emails with an international well control expert (Wild Well), and searches of well safety and regulatory websites indicate research is needed to inform safe and effective well control methods involving acid gas release. While there is published literature on acid gas system surface design and reservoir / aquifer considerations for acid gas injection, papers on acid gas wells are extremely limited and until 2018 did not address the thermodynamic behaviour of acid gas during an uncontrolled release. To illustrate:

1. Lynch *et al* (1985) describe a dynamic kill of an underground blowout while drilling a well for a naturally occurring CO_2 deposit.
2. Galic *et al* (2009) present an initial attempt at modelling a conceptual CO_2 capture and storage system, comprising an onshore power plant CO_2 source, a transport/distribution pipeline and multiple offshore wells injecting into one or more depleted gas reservoirs in the North Sea.
3. Mireault *et al* (2010) present some wellbore dynamics for acid gas injection well operation.
4. Mireault *et al* (2010) present some wellbore dynamics for CO_2 sequestration well operation.

The rarity of incidents is encouraging but the apparent worldwide lack of knowledge to regain control is concerning.

Scope of Work

Identified gaps in existing literature and a shortage of acid gas subject matter expertise led the BC Oil & Gas Commission and the BC Oil and Gas Research Innovation Society (BCOGRIS) to lend its support to this research to:

a) Comprehensively document the thermodynamics of the system and potential acid gas release behaviours and risks and
b) Identify and evaluate potential well control measures that address the unique conditions and risks associated with an acid gas release.

The study objectives include:

- Increasing the understanding of the unique thermodynamic aspects of acid gas releases and associated challenges of safe mitigation.
- Identifying potentially effective acid gas release control methods and equipment for two release scenarios (low rate and medium-high rate) for further discussion and evaluation.

Methodology

To fulfil part a) of the work scope, in late 2017 the BC OGC encouraged the author to publish a paper on the thermodynamic behaviour of acid gas during an injection well blowout. Based on the author's experience in the design, modelling, operation, maintenance and repair of acid gas injection wells, phase behaviour and wellbore modelling were undertaken using the IHS-Markit VirtuWell™ nodal analysis software combined with the VMGThermo EOS property package. The work was presented in a paper titled "Emergency Response Planning for Acid Gas Injection Wells" at the 7th International Acid Gas Injection Symposium held in Calgary Alberta; May 25 - 28, 2018. The paper is included in *The Three Sisters*, a soon-to-be-released compendium of papers from the symposium (see *Mireault*[6]).

By late 2018, it was realized that an uncontrolled release from a depleted, low pressure reservoir might yield different behaviour from the previously modelled scenarios. However, by then the vendor no longer supported coupling the VirtuWell™ software with the VMGThermo package to model acid gas systems. Therefore, the depleted reservoir case was modelled using the VMG Symmetry software platform, which encompasses the VMGThermo property package and Pipe, the multiphase flow modelling software. The VMG Symmetry suite was selected because of its proven track record in accurately modelling acid gas properties and phase behaviour, as well as multiphase flow. While the industry more commonly uses the Pipe software to model multiphase flow in pipelines, particularly those with significant elevation changes, in the hands of an experienced user it proved quite capable of modelling acid gas wellbore behaviour.

Part b) of the work scope was accomplished through direct discussion and meetings with the major well blowout recovery companies in Alberta and BC. The discussions reinforced that the industry does not currently have specific procedures or equipment to address the unique challenges presented by an acid gas well blowout. Further, it quickly became apparent that development of new, appropriate procedures and equipment will require a collaborative effort between multiple areas of technical and operational expertise.

It also became apparent that detailed knowledge of the escaping acid gas plume behaviour will be critical to the development of effective AG well blowout emergency response and well recovery procedures. Accordingly, Questor Technology Ltd. was approached for their proven expertise in modelling emission concentrations, particularly H_2S, SO_2 and CO_2 from acid gas sources. Questor is a well-established incinerator manufacturer that has:

- Developed incinerators with >99.99% combustion efficiency.
- Developed proprietary software to quantify emission concentrations from a source such as an incinerator, flare stack, or damaged wellhead.
- Incinerators in acid gas and tail gas clean-up service that successfully maintain emissions within the prescribed limits for regulatory compliance.

Questor has confirmed their willingness to be involved in future research as the work progresses.

ACID GAS THERMODYNAMIC BEHAVIOUR

Medium to High Release Rates

In a well blowout, acid gas effluent at reservoir temperature and pressure flows from the reservoir through the wellbore and is released into the atmosphere from a failed wellbore below the casing flange or at wellhead / BOP stack or piping immediately connected to it. For the aquifer/reservoir temperature and pressure conditions encountered in British Columbia/ Western Canada, the resulting pressure drop to atmosphere yields a very cold to extremely cold exit temperature for the escaping acid gas over a wide range of acid gas compositions (See Table 1).

Depth	Conditions at Bottom of Wellbore			Acid Gas Escape Temperature at Ambient Pressure °C		
m	% of Hydrostatic Gradient	kPaa	°C	78/20/2 % $H_2S/CO_2/C_1$	49/49/2 % $H_2S/CO_2/C_1$	20/78/2 % $H_2S/CO_2/C_1$
1000	51%	5000	50	-67.2	-16	-8.1
1000	82%	8000	50	-70.2	-77.5	-68.6
1500	48%	7000	68	-66.8	-20.7	-7.8
1500	82%	12000	68	-69.2	-77.3	-86.5
2000	46%	9000	85	-66	-20.5	-3.4
2000	82%	16000	85	-68.5	-76.5	-86.4
2500	45%	11000	100	-66.7	-17.6	2.4
2500	82%	20000	100	-68	-75.9	-83.2
3000	48%	14000	120	-57.4	-8.8	13.5
3000	82%	24000	120	-67.5	-74.9	-53.2

Table 1 Acid Gas Escape Temperature at Surface *from Mireault*[6]

The calculations assume adiabatic expansion of the acid gas as it travels up the wellbore because:

- Vertical wellbores make poor heat exchangers. The amount of heat that is transferred to the gas is small and can be ignored for practical purposes.
- Short gas residence time in a blowout scenario further limits heat transfer.

To verify the assumption, wellbore modeling was undertaken to assess whether the escaping acid gas temperature could increase significantly during a blowout via wellbore heat transfer. Plots of acid gas temperature vs well depth for 6 of the blowout cases (arbitrarily selected) through 88.9 mm tubing illustrate the validity of the approximation (Table 2 and Figure 1).

Depth	Conditions at Bottom of Wellbore			Blowout Rate		Acid Gas Escape Temperature at Ambient Pressure °C		
m	% of Hydrostatic Gradient	kPaa	°C	$10^3 m^3/d$	m^3/sec	78/20/2 % $H_2S/CO_2/C_1$	49/49/2 % $H_2S/CO_2/C_1$	20/78/2 % $H_2S/CO_2/C_1$
1000	51%	5000	50	238	2.75	-67.2	-16	-8.1
1000	82%	8000	50	455	5.27	-70.2	-77.5	-68.6
1500	48%	7000	68			-66.8	-20.7	-7.8
1500	82%	12000	68			-69.2	-77.3	-86.5
2000	46%	9000	85	386	4.47	-66	-20.5	-3.4
2000	82%	16000	85	520	6.02	-68.5	-76.5	-86.4
2500	45%	11000	100			-66.7	-17.6	2.4
2500	82%	20000	100			-68	-75.9	-83.2
3000	48%	14000	120	318	3.68	-57.4	-8.8	13.5
3000	82%	24000	120	571	6.61	-67.5	-74.9	-53.2

Table 2 Cases Selected for Wellbore Modeling *from Mireault*[6]

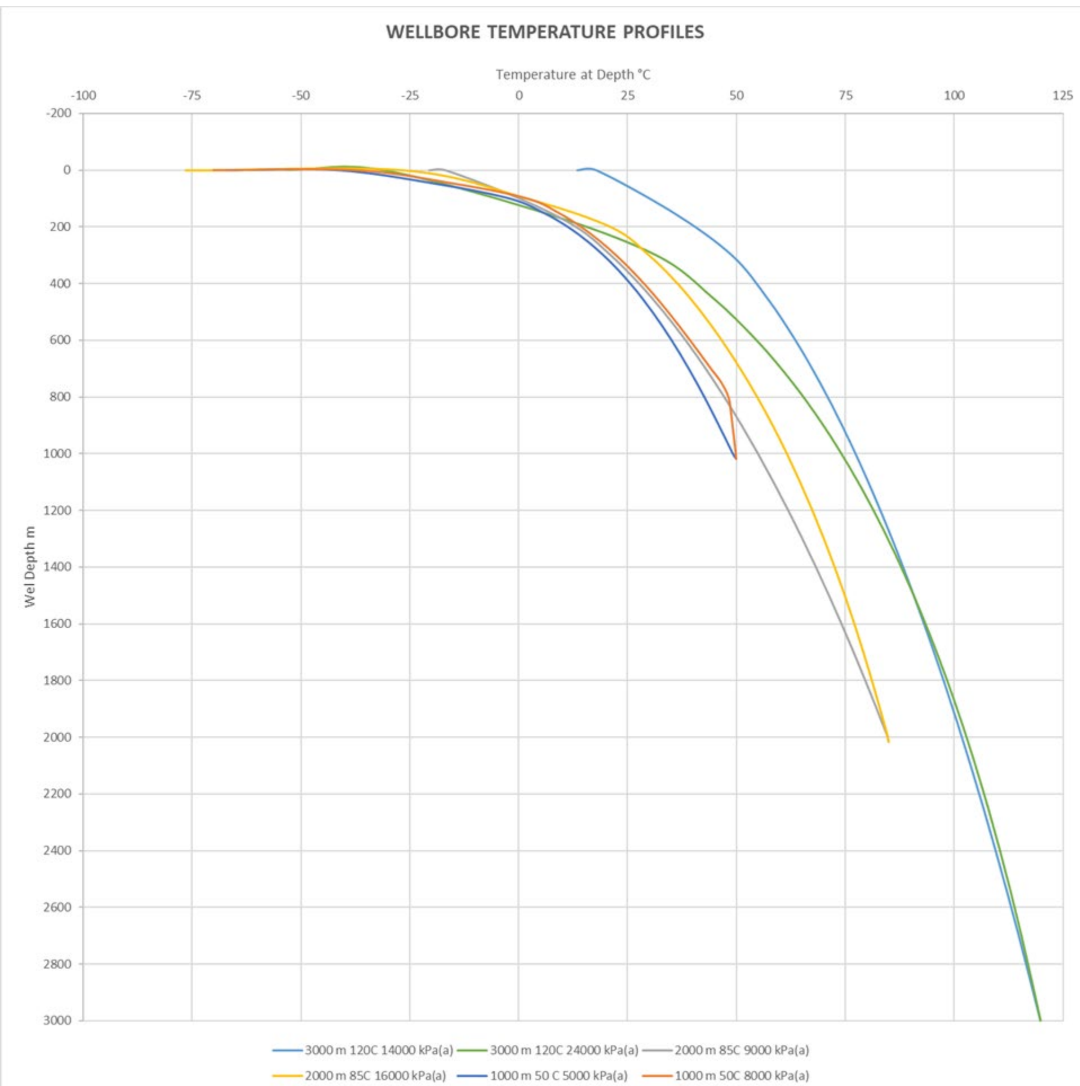

Figure 1 Acid Gas Temperature vs Well Depth in a Blowout *from Mireault*[6]

The profiles show that in all cases, the majority of cooling occurs within 150 to 300 m of the wellhead. Further, with a capacity of about 1.14 m^3 (0.0038 m^3/lineal m) in the upper 300 m of 88.9 mm tubing, the gas residence time is fractions of a second; providing little opportunity for heat transfer.

Additional observations from the modeling include:

- All other things being equal, increasing bottomhole pressure increases a well's blowout release rate, which means a larger surface volume in a shorter period of time.
- In all cases a higher initial pressure further decreases the exit gas temperature. Further, in some cases the temperature disproportionately decreases relative to the incremental increase in reservoir pressure.

Phase envelopes for the 3 acid gas compositions – 78/20/2, 49/49/2 and 20/78/2 % $H_2S/CO_2/C_1$ and the 10 bottom of wellbore conditions are presented as Figures 2, 3 and 4. Bottom-of-wellbore conditions for each gas composition that are above or on the isenthalpic expansion line shown in the Figures have a similar acid gas escape temperature; for 78% H_2S about -68°C, for 49% H_2S, -76°C, for 20% H_2S, -86°C.

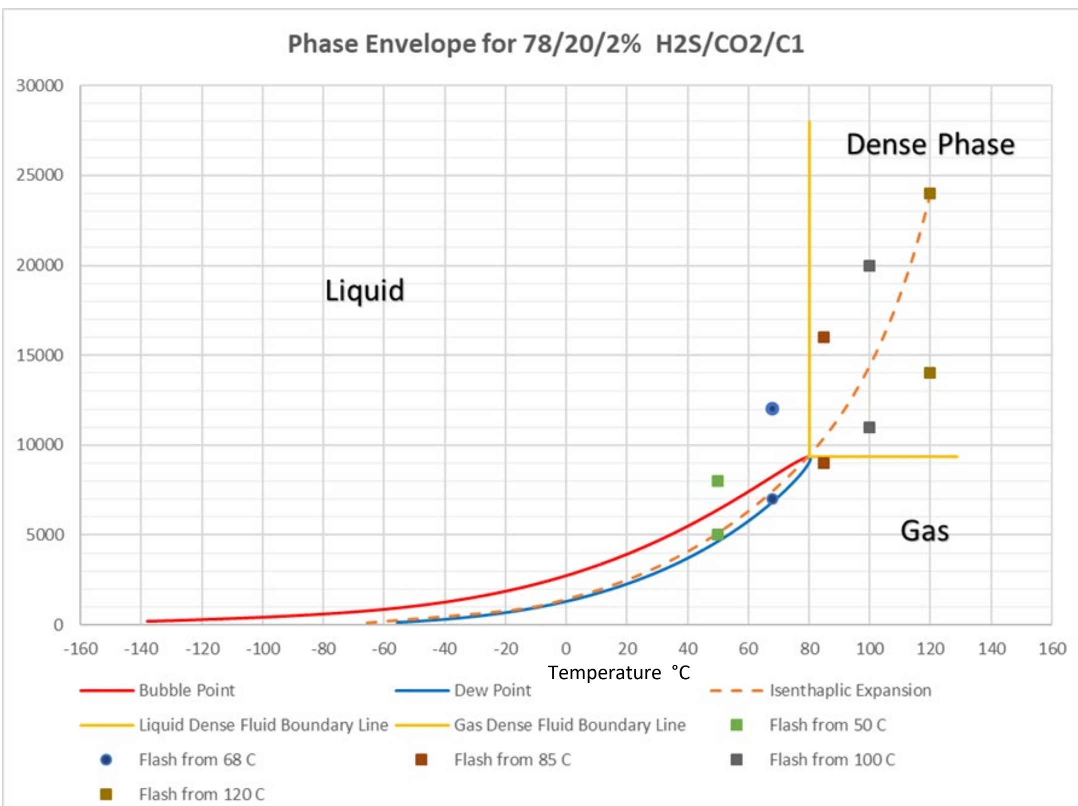

Figure 2 78/20/2% Phase Envelope with Isenthalpic Expansion Bottomhole Conditions *from Mireault*[6]

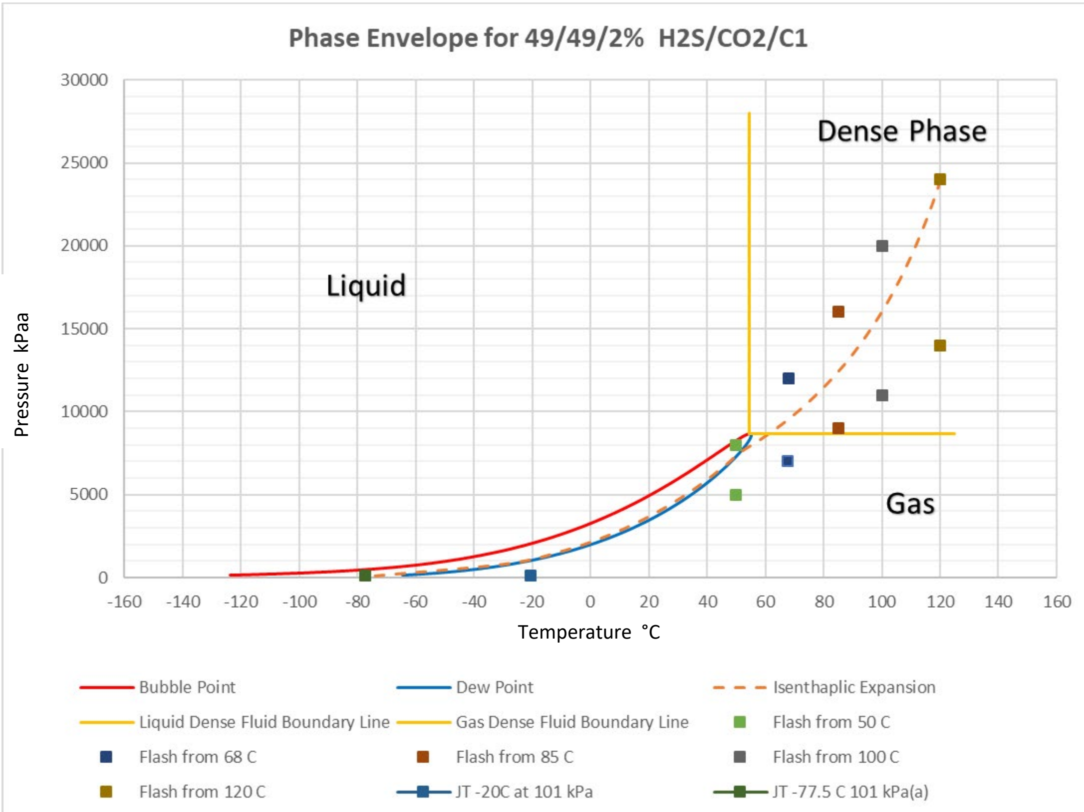

Figure 3 49/49/2% Phase Envelope with Isenthalpic Expansion Bottomhole Conditions *from Mireault*[6]

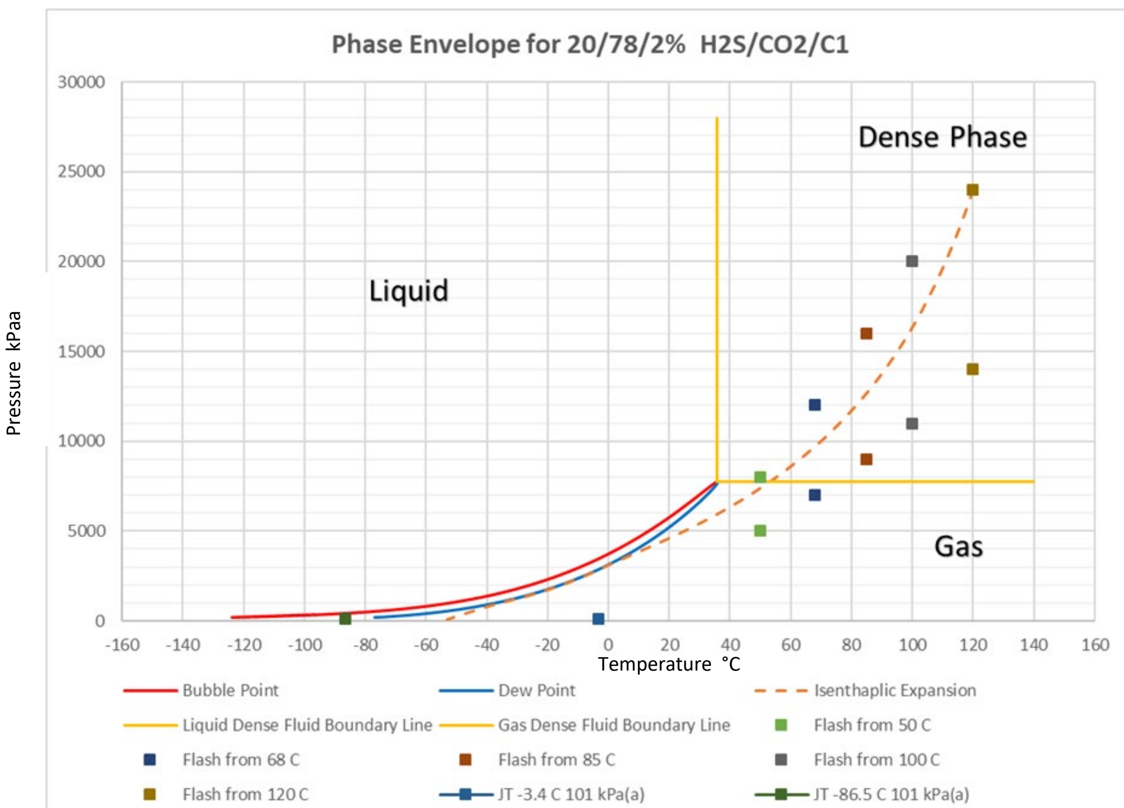

Figure 4 20/78/2% Phase Envelope with Isenthalpic Expansion Bottomhole Conditions *from Mireault*[6]

Bottom-of-wellbore conditions that are some distance below the isenthalpic expansion line transition directly from dense phase to gas. Without the additional cooling created by a liquid to gas phase change, the surface escape temperature is warmer, as shown in Table 2 and illustrated by the J-T endpoints presented in Figure 3 and Figure 4.

Low Release Rate

Warmer acid gas surface escape temperatures can be expected if a blowout occurs from a depleted (<5000 kPaa) reservoir, where acid gas is gas phase at reservoir conditions. As an example, the VMG Symmetry software suite was used to model a 2700 m deep injection well with:

- Reservoir temperature of 85° C and depleted reservoir pressures of 828 and 2280 kPaa.
- Acid gas composition of 78/20/2% $H_2S/CO_2/C_1$
- 73 mm tubing and 178 mm production casing
- An AOF of 3.41 and 24.01 $10^3 m^3/d$ at reservoir pressures of 828 and 2280 kPaa, respectively.

Operating points for the 4 blowout scenarios are visually presented on an overlay of the tubing/casing performance curves against the IPR curves (Figure 5).

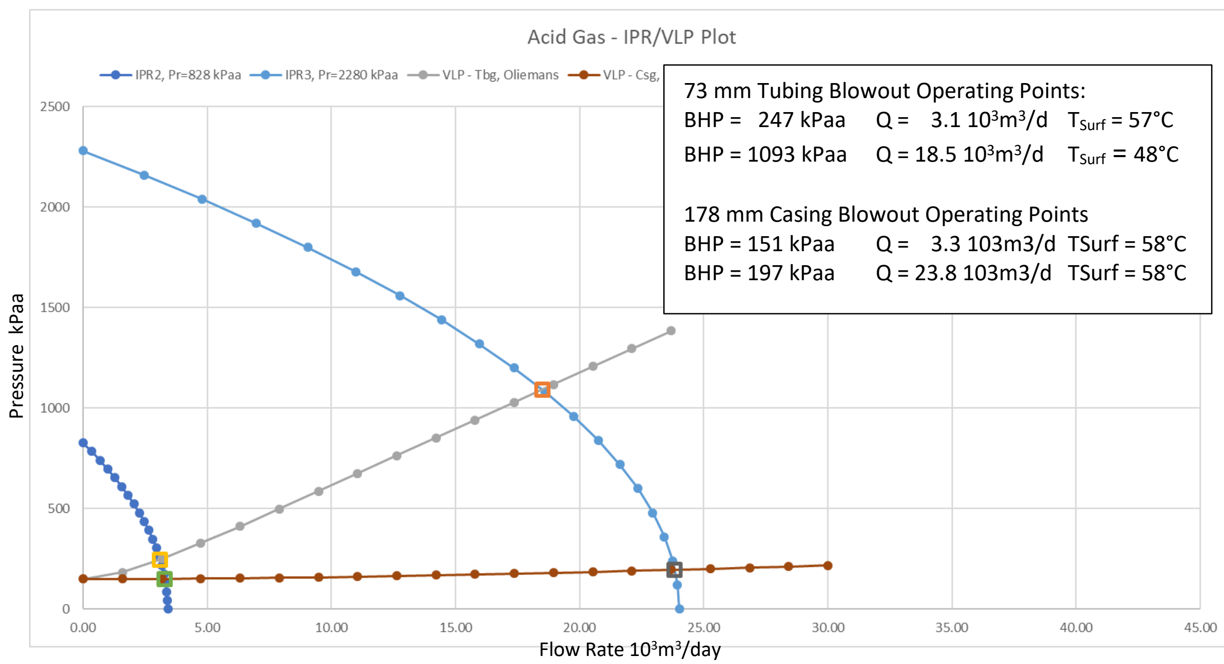

Figure 5 Depleted Reservoir Low Blwout Rate Example

Exit acid gas temperatures of 48, 57 and 58°C are below the 85°C reservoir temperature but are well above the sub-zero temperatures associated with releases at higher reservoir pressures.

Escape Cloud Behaviour and HS&E Risks

The author's experience with plume modeling predictions for acid gas blowouts comes from working with plume modeling companies in studies done for acid gas disposal well applications for the Texas Railroad Commission. With gas exit temperatures of -50 to -80°C, simulations consistently indicated the plume would rise only a short distance into the air and then fall back to earth; as expected for heavier than air compounds.

Plume escape modeling for a depleted, low release rate reservoir has yet to be undertaken. A lower release rate means a smaller plume volume for a given time period. However, the lower exit velocity reduces the vertical distance that the effluent rises before falling back to ground level. Escape temperatures in the 48 to 58°C range reduce the density of the fluid at the point of escape but ultimately, it remains a heavier than air gas that will fall back to earth. The resulting cloud height and dispersion behaviour is unknown and requires further investigation.

No significant accidental atmospheric releases of waste acid gas have occurred in NEBC but it is prudent to understand potential behaviour. Anecdotal evidence provides comparative outcomes to the wellbore and plume modeling predictions:

- Lynch *et al*[1] report frozen chokelines and casing valves and "softball size chunks of solid CO_2 spewing hundreds of feet into the air" out of surface fissures that resulted from an underground blowout while drilling a CO_2 reservoir in the Sheep Mountain Unit, Huerfano County, Colorado.
- An informal presentation[5] on a blowout from a CO_2 injection well that was part of an EOR scheme at a temperate latitude in Eastern Europe showed photos of a stable blanket of CO_2 that reached from ground level to the tops of the deciduous trees (perhaps 10 to 12 m) in hilly, rolling farmland.

Limited plume loft infers little mixing between the escaping effluent and air to dilute concentrations of H_2S and CO_2.to safe limits. An H_2S concentration of 100 ppm is considered immediately dangerous to life and health. However, high CO_2 concentrations are also a concern. According to one safety data sheet, a 10% CO_2 concentration can cause unconsciousness in 1 minute or less (http://www.generalair.com/pdf/Safety%20Topics/Carbon%20Dioxide%20Asphyxiation.pdf).

Ignition is the industry's immediate response to the toxicity of an uncontrolled sour gas release. The heat generated increases plume loft, which further mixes, dilutes and disperses the combustion products over a very large area to concentrations that are not immediately life threatening (though they may be uncomfortable). The fire also continuously draws fresh air to the well, allowing blowout control personnel and equipment to access the wellsite.

However, ignition is not a reliable solution for an escaping acid gas plume because:

- The CO_2 concentration of the acid gas may be such that it can't be ignited.
- The flammable limits for H_2S are 4 to 44% by volume in air. Thus, an escaping acid gas cloud may be too lean or too rich to ignite, or perhaps only isolated "pockets" within the cloud could be ignited.
- Although H_2S vaporizes readily (its boiling point is -60°C) its auto ignition temperature is 232°C. (https://en.wikipedia.org/wiki/Hydrogen_sulfide) If H_2S can be ignited but is unable to heat the area around the flame to at least 232°C, combustion will not sustain itself.
- Even if ignition can be sustained, insufficient heat may be generated to dilute and dissipate CO_2, SO_2 and unburnt H_2S concentrations to safe ground levels - the heating value of H_2S is 6545 Btu/lb vs 21,537 Btu/lb for methane. The low heating value of H_2S is why incinerators require supplemental fuel gas to meet emission standards. Exposure to 100 ppm of SO_2 or H_2S is considered immediately dangerous to life and health. https://www.atsdr.cdc.gov/toxfaqs/tf.asp?id=252&tid=46

If acid gas cannot be ignited, the consequences of a damaged wellhead at the center of a toxic, stable and growing ground level cloud of acid gas could be severe under any scenario. How quickly the cloud blankets the surrounding area depends on the release rate, while the thickness of the blanket and its direction of travel would likely be influenced by factors that include air temperature, wind conditions, topography and vegetation. For example:

- Mountainous terrain may tend to create a very thick blanket and direct its expansion along the length of a valley.
- Treed terrain may trap the blanket and reduce or delay any dilution and dissipation from the wind and sun.
- Open prairie or an offshore blowout might reduce the depth of the blanket but allow it to spread more quickly over a larger area.

ACID GAS BLOWOUT RECOVERY

Basic Concepts

The steps in conventional blowout recovery operations can be broadly categorized as follows:

1. Initial wellsite reconnaissance and assessment.
2. Recovery Plan Development and Equipment/Material/Personnel Logistics
3. Site Equipment Preparation, Fabrication and Testing – (e.g. heat shields, water supply/storage, fire hoses, pumps, etc...)
4. Preparation for and Removal of Damaged Wellsite Equipment and Piping
5. Fire Extinguishing (temporary) and Installation of New Well Control Equipment (typically BOP stack)
6. Testing of the newly installed pressure control equipment leading to shut-in of gas flow.

The same sequence is assumed as a starting point to develop recovery procedures for an acid gas blowout. However, points to consider in developing acid gas recovery procedures include:

- Acid gas blowouts from the initial injecting well(s) should only be cased hole blowouts that occur during injection or well servicing operations, since well drilling occurs prior to the start of injection. The exception is if subsequent wells are deliberately or unknowingly drilled into an existing acid gas reservoir plume.
- Procedures to protect recovery support personnel and the general public from a ground level cloud of immediately toxic gas will be different from conventional procedures.
- An initial reconnaissance and damage assessment are essential first steps in any recovery operation.
- Ultimately, a well has to be accessed in order to replace damaged valving to secure the well.
- Although erosional velocity damage would still be a concern, if there isn't a fire at the wellsite there may be less damage to above ground BOP /wellhead valves and piping, as well as any service equipment on location at the time of the blowout, unless the loss of wellbore integrity is below the casing flange.
- Explosion-proof electric or hydraulic motors can operate in an oxygen deficient atmosphere. The challenge is providing an adequate power supply.

Initial Reconnaissance

Initial reconnaissance is conventionally done by donning an air pack and walking through the wellsite lease. With an acid gas environment, a better approach might be a combination of:

- A camera-equipped drone for an initial fly-over of the wellsite and for real-time monitoring of the escape cloud's location, direction and rate of advance.
- A remotely operated robot for "up-close" assessment and possibly light duty recovery operations (e.g. rotate valve handle).

The power requirements for reconnaissance work are low enough to be supplied by batteries; creating mobile, self-contained units. If successful, remotely operated units could avoid or at least minimize exposure of recovery personnel to the acid gas blanket.

Heavy Equipment for AG Recovery Operations

The large power requirements for heavy equipment including bulldozers, cranes, water pumps can in theory, be supplied by electric motors connected (with very long cables) to a power generating system located a safe distance from the wellsite. TransAlta uses electric shovels/excavators to mine coal for power generating plants near Edmonton (https://www.transalta.com/facilities/mines-operation/highvale-mine/), so the technology might be adapted for wellsite blowout recovery operations. Another potential technology might be the hydraulic motors/options used for undersea work, which provide the benefit that there is no possible source of spark ignition.

While service rigs that are on the well at the time of a sour gas blowout are invariably destroyed by the resulting fire, an onsite service rig during an acid gas blowout may not suffer the same fate. An electric drive rig connected to remote power generation might still be operational for subsequent recovery operations.

Another area for investigation is the degree to which heavy equipment (including the rig) could be automated. While 100% remote operation may not be achievable, the minimum objective would be to prevent simultaneously exposing personnel to the hazards of moving equipment and rotating machinery in a toxic atmosphere.

RECOMMENDATIONS

The following areas require further investigation to develop recovery procedures for an acid gas blowout:

- Acid Gas Escape Cloud Modelling, including behaviour under attempted ignition.
- Personnel Training
- Blowout Recovery Procedure Development and Testing
- Blowout Equipment Development and Testing

While not part of this study's scope, development of funding arrangements for each area of study will be a necessary part of the process. In particular, the level of investment required for development and field testing of equipment and recovery procedures, as well as personnel field training cannot be borne by a service company, given the uncertain and infrequent need for such infrastructure.

Acid Gas Escape Cloud Modelling

Further insight on the behaviour of an escaping cloud of acid gas is required for emergency planning; to protect the public and personnel and develop wellsite blowout recovery procedures. Questions for simulation modelling include:

- The behaviour of an escaping cloud in different terrains and at different well locations within a given terrain. What shape is the cloud likely to take; long and narrow, round or irregular? What might be the height of the cloud? What factors significantly influence cloud shape and travel over the area? Is there an advantage to locating the well at the base of the valley, near the crest or on a high plateau?
- Does acid gas composition significantly affect cloud behaviour?
- Can the escaping effluent be ignited? What is the impact of ignition? At what concentration of CO_2 is ignition no longer possible?
- How quickly does a cloud travel and what are the important factors that determine travel speed?
- How quickly can a cloud change direction and what are the significant factors that affect direction?
- Should acid gas wellsites have 2 different access /escape routes pre-built, to deal with the variability in cloud formation and migration? Should there be a minimum arc radius between the routes? How will evacuation of residents or tenure holders be handled?

Personnel Training

Two (2) levels of training are recommended as follows:

1. For those who work around the wells on any kind of basis BEFORE a catastrophic event, including operators, field foremen and well maintenance and rig service personnel. Training would be centered around personal safety, leak detection, best operating practices, example situations that could result in a loss of well control, and the basics on how to recognize a problem, who to call and exactly how deadly problems could be.
2. The second level would be geared toward the recovery team and those who would have input/participation of any kind in a recovery operation including operator company office and field emergency response personnel, and OGC personnel. Training for this level would include the level 1 subjects plus:
    a) Wellsite initial reconnaissance and assessment – equipment and procedures
    b) Damaged wellsite equipment and material removal procedures
    c) Specialized on-site recovery equipment and operating procedures
    d) Well blowout control equipment and installation procedures

It is envisioned that training would be delivered via a combination of classroom instruction and field exercises, with rental of 3rd party facilities for the field component of the course(s).

A third course or seminar may also be appropriate for municipal / regional first responders (police, ambulance crews, fire departments, hospital staff), and other non-industry personnel who would become involved in the event of an emergency.

Development of Recovery Equipment and Procedures

Once funding arrangements are in-place, Safety Boss, an industry leading well blowout recovery company that services Alberta and BC, has indicated their willingness to lead / be involved with the development and testing of specialized blowout recovery equipment and procedures, as well as Level 2 training for emergency response personnel.

Prototype development and testing would necessarily go hand-in-hand with course development for the level 2 training, and would similarly require rental of 3rd party facilities. One possibility is the Energy Safety Canada Training facility at Genesee, which normally provides hands-on training in the controlled ignition of a vapour plume. Ultimately, development of test objectives and detailed test procedures should lead to a full-scale test exercise of the equipment and procedures.

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Acknowledgements

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