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Application and Value of Geothermal Well Reliability Data

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Keywords

Thermal well, geothermal well, thermal oil recovery well, failure, integrity, reliability, data, risk, risk-ranking model.

ABSTRACT

Statistical analysis of even relatively sparse and high-level well reliability (failure) data can generate metrics and insights. Failure rate values can be used by Operators, technology providers and Regulators to predict project risks, production and asset availability and uptime, and the relative risks between wells as a function of location, geology, age, technology deployed and practices. Probability of failure values for key components and systems can be combined to develop estimates of predicted well damage and failures, required workover frequency, and asset inspection, maintenance, repair and decommissioning costs. Unfortunately, in most applications, well reliability (failure) data is typically sparse, incomplete, or non-existent, in part due to the cost, risks and complexity of diagnosing, measuring and tracking well damage and failures. In some cases, the only publically available sources of data are held in Regulator body databases because regulations require Operators in many regions to submit failure data of key well components, such as production casing and cement sheath failures (surface casing vent flows and gas migration events), which impact environmental, safety and resource priorities of the state, province or country.

In this paper, the value of tracking well reliability data will be presented. The types and different levels of reliability data will be described, as well as the potential uses, applications and impact that such information and the calculated metrics can provide. Illustrative examples from the geothermal energy and thermal-enhanced oil recovery industries will be used to: show the forms of the data available; illustrate some of the challenges obtaining, processing and extracting value out of such data; demonstrate apparent differences between wellbore reliability statistics of the geothermal and thermal oil recovery applications; and examine potential cross-over learnings from one industry to the other.

1. Introduction

Most industries are capitalizing on the advances in data gathering, analysis, simulation and modeling capabilities to identify opportunities for: improvements in investment options; increased process efficiency; reduced energy and resource demands; reductions in unexpected failures and associated impacts on equipment and asset uptime; reduced demands for manpower;

improved safety and environmental impacts through preemptive failure prediction and prevention; and overall improvements in the economics of their business through reduced capital and operating costs. The upstream sectors of the oil and gas and geothermal energy industries, and in particular the wellbore operational and maintenance components, however, have been slow to capitalize on these advancements. This has in part been due to a lack of availability of high-quality reliability or failure data, and recognition by the upstream sectors in the significant potential impacts that improved use of such data can offer.

In this paper, some of the potential impacts that may be realized from the broad adoption and improvements in the collection, quality, analysis and application of wellbore reliability data to the upstream oil and gas and geothermal energy industries are highlighted. Examples of the thermal oil recovery and geothermal well reliability data sources, reliability indicators, and some of the current challenges and shortcomings are noted. While the focus in this paper is on the reliability of the production casing strings of these wells, such methods could be readily applied to other well barriers, such as the cement sheath and wellhead, and to other key components, such as sand control systems, downhole pumps, and monitoring and control systems. Some of the different forms of predictive and risk-ranking models are noted, and an example of one simple approach, which includes the use of field data to develop parameter weighting coefficients, is illustrated.

2. Background

2.1 Data and the Digital Revolution

Combinations of historic and real-time data used to develop improved models on the condition, performance, and remaining life of equipment and systems are becoming increasingly more common with the acceleration of data volumes and the ability to analyze this data(1). This Fourth Industrial Revolution, or Digital Revolution (World Economic Forum 2018, World Economic Forum 2017), is recognized as offering significant opportunities in almost every industry, from manufacturing, transportation, finance, agricultural, petrochemical and energy, to healthcare, education, defense, environmental monitoring and communication. In many of these industries, the benefits being realized include: system optimization in terms of improved efficiency, production quality, uptime and availability; reductions in the number of staff required, particularly in the execution of more repetitive and routine tasks; improved safety and reliability; reduced scheduled maintenance; reduced costs; and improved economic, energy intensity and environmental metrics. This revolution is taking place with the simultaneous advancements in data, connectivity, computational and electronic technologies, and monitoring and control systems, and is being spurred by the increasing global competitive nature across all industries. Also common to many of these industries making use of this data and associated technologies is that this is being done in combination with oversight or captured experience of Subject Matter Experts (SMEs).

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[1] 'Big data' volume, velocity, variety and veracity, and the ability to rapidly acquire and analyze data with continual advances in sensors, data transmission, storage and broad access, computational speed, analysis algorithms, and skilled personnel.

The energy industry, in particular the upstream oil and gas and geothermal sectors of the industry, generally recognizes the potential benefits of digitization, the improved use of data and advancements in predictive models. For example, in a recent study of the business and societal impacts of digital transformation in the oil and gas industry (World Economic Forum 2017), it was projected that the financial impact to the oil and gas sector over the next decade was on the order of \$170 billion in savings for customers, \$10 billion in productivity improvements, \$30 billion in reducing water usage, and \$430 billion from lowering emissions. Furthermore, the projected environmental impacts include reducing CO_2-equivalent emissions by approximately 1300 million tonnes, reducing water use by about 800 million gallons, and avoiding the spill and release of about 230,000 barrels of oil.

2.2 Migration from Downstream to Downhole

While the use of data, advanced regression analysis (analytics) and gradients of data-driven and physics-based system models are quite mature in the downstream and midstream areas of the oil and gas(2) and energy supply sectors (e.g., surface pumps, turbines, and energy transmission systems), the migration to the upstream sector, and in particular to the downhole wellbore and equipment components, has been slow. Advanced sensor and optimization methods are making their way into the wellbore construction with drilling rig automation, predictive event modeling (e.g., kick and stuck pipe events, drill string whirl and vibration) and optimization of penetration rates and drilling time (Liu et al. 2014, Mirani and Samuel 2016, Baumgartner 2017, Karimi and Darabi 2018). Some advancements are also being made in mature field reservoir optimization (Brown et al. 2017) and the operation of wells, such as in the prediction of artificial lift failures (Sheldon et al. 2017, Patri et al. 2014) and well shut-down events (Lek 2017, Zborowski 2018). In the geothermal sector, data analysis/analytics is being used to aid in resource development identification and energy process optimization (Westwick-Farrow 2012, ADI Analytics 2018, Nevis Geothermal 2018).

However, despite this progress, there remains little advancement in the use of data and improved modeling in the areas of wellbore integrity, reliability and availability in the oil and gas and geothermal sectors. Some of the apparent reasons for this appear to be: the lack of suitable volumes of consistent, high-quality data (Davies et al. 2014, Lohne et al. 2016); limited experience and familiarity with the use of such data and damage models in predicting wellbore failures (Lohne et al 2016); the challenges associated with collecting downhole data in high-temperature oil and gas and geothermal wells (Thorhallsson 2003); and the lack of focus and investment of resources in these sectors to make advancements in these areas. Some of the challenges associated with obtaining, processing and extracting value out of such data will be presented in the following sections. Examples of thermal recovery oil well and geothermal well data are presented, and discussions on how such data can be used to improve the well designs and manage resources (capital and human) in optimizing wellbore integrity, reliability and availability.

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[2] Hale (2015) and Santos et al. (2015).

2.3 Motivation for High Reliability and Availability in Geothermal Wells

High availability and reliability are important contributing factors toward the economics and asset integrity (and in turn the associated safety and environmental containment(3)) of geothermal energy wells, in particular in projects where well inventories are being kept to a minimum to optimize economics (Thorhallsson 2003). The significant technical challenges(4) and relatively high costs associated with drilling geothermal wells, reported to often be between two and five times greater than oil and gas wells of the same depths (Augustine et al. 2006), and the high cost of the wells relative to the total cost of the project(5), suggest that maintaining the minimum number of excess wells in the well inventory of a geothermal project would tend to have a big impact on overall project economics. Lohne et al. (2016), for example, noted that, in an environment of increased geothermal energy well costs, a reliability-based design approach is suggested to obtain a geothermal well design optimized for construction costs, deliverability, availability and well-life. Lohne et al. (2016) also noted that: (i) compared with the petroleum sector, the geothermal industry lacks the maturity and the volume of data, in part due to the focus more on reservoir development risks than on well life in the geothermal sector, and the lack of regulations in many regions enforcing the tracking of information and risk assessments for geothermal wells; and (ii) the geothermal sector could look to the petroleum sector for guidance on the risk analysis and reliability modeling methods and the associated types of data that would support such methods.

3. Thermal Well Damage Mechanisms and Influential Factors

Thermal oil recovery wells, such as the wells used to inject steam and produce oil using the Steam Assisted Gravity Drainage (SAGD) and Cyclic Steam Stimulation (CSS) recovery methods applied in the Western Canadian oil sands and the steam flood and CSS wells used in the California heavy oil regions, and geothermal energy wells share a number of common well design, operational and integrity characteristics (Petty et al. 2009, Teodoriu and Falcone 2009, Droessler et al. 2017). Some of the common thermal well damage and failure mechanisms, which can occur in both thermal oil recovery and geothermal wells (Snyder 1979a, Snyder 1979b, Southon 2005, Lohne et al. 2017), include:

- *Casing damage*: parting, collapse, and burst of the pipe body; parting at connections; near-surface oxidative corrosion; environmental-induced cracking (sulfide stress

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[3] As noted by Summers et al. (1980), geothermal resources are often in seismically active, highly fractured regions and produce fluids with compositions of components, such as arsenic, boron, lead, and mercury, which greatly exceed the drinking water and biotic toxicity levels. Loss of containment due to failure of well barriers and migration of such fluids through fractures or along wellbores (e.g., behind casing in uncemented or poorly cemented regions) to aquifers and near-surface regions could result in significant health, environmental and water quality consequences.

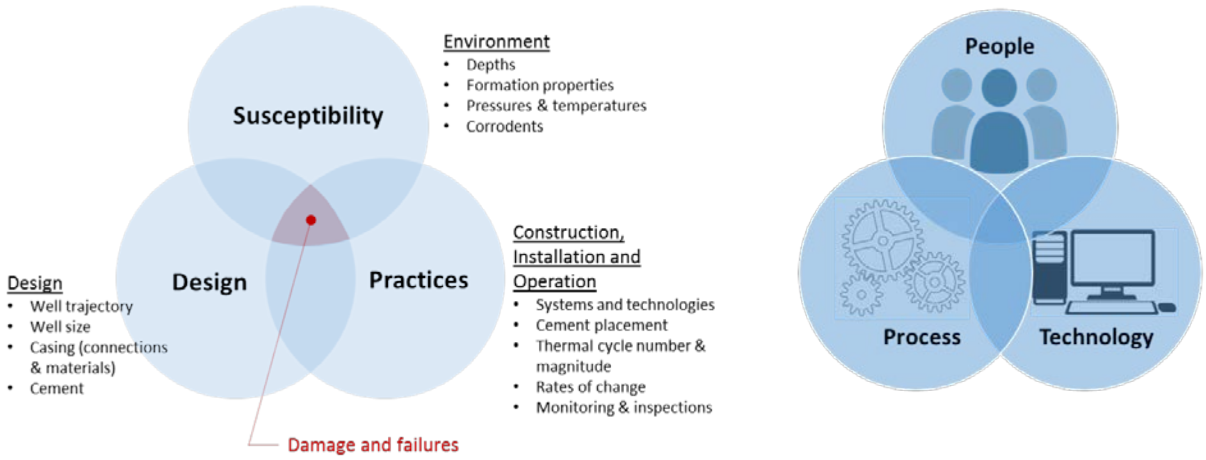
[4] Such as added non-productive time during drilling due to lost circulation events, as noted by Cole et al. 2017.

[5] For example, the wells account for between 30% and 50% of the total asset value for geothermal electric generation facilities, with geothermal power wells in Iceland costing between US$1.5 million and US$3 million (Thorhallsson 2003). Similarly, well costs account for between 42% and 95% of the total costs for an Enhanced Geothermal System (EGS) project (Augustine et al. 2006).

corrosion cracking); caustic cracking; buckling; trapped annular fluid collapse; formation movement induced shear; wall loss during drilling;

- *Cement damage*: flow through poorly placed cement; gas or mud channels; cracking; creation of casing-to-cement sheath and cement sheath-to-formation annuli due to thermal-induced casing expansion, pressure-induced expansion, elevated stress and temperature effects; cement and formation creep under elevated temperature and stress; degradation due to temperature (retrogression); chemical attack and corrosion; and
- *Wellhead, valves and flow line damage*: solid particle and droplet-induced erosion; corrosion; excessive thermal or differential expansion (e.g., expansion of excess grease inside valves).

Many of these damage mechanisms require a combination of environmental conditions, system design characteristics and operational conditions to occur (see Figure 1). Sulphide Stress Cracking (SSC), for example, requires sufficient concentration of hydrogen sulfide, temperatures below approximately 80°C, and tensile stresses. Steps can be taken in the design (material selection and stresses), operation (tensile-induced stresses due to wellbore cooling, and the availability of wet hydrogen sulfide) and oversight (people and monitoring) to manage or even eliminate contributing factors and potential occurrences of SSC-induced damage and failures.



(a) Damage mechanism susceptibility factors (b) Mitigation methods and actions

Figure 1: Wellbore damage mechanism susceptibility factors and methods to mitigate damage to improve well integrity and availability.

4. Sources and Application of Thermal Well Reliability Data

This section provides a brief overview of some of the different levels of reliability information, where well reliability information can be used in assessing well risks, and some of the sources and examples of identified well reliability data for thermal oil recovery and geothermal wells.

4.2 Levels of Reliability (Failure) Information and Application to Well Design and Integrity

As illustrated in Figure 2, different levels of well reliability (failure) data and information offer different levels of analysis, model development, and direction related to wellbore design, potential failures and associated factors, predictive failure prediction, and risk assessment. Failure frequency data on its own provides a means to track and compare overall numbers, but if the well population is changing with time, the frequency alone does not offer insights into the failure rate or probability with time. For this, the number of failures per population exposed or at risk is required. Failure rate values and trends can be compared over time, benchmarked between operations, and used in risk assessments. If additional application, system design, operational and failure characterization information is available, influential factors can be identified and attribute-based damage or failure models can developed. Furthermore, if consequence information is collected, improved reliability-based design and maintenance methods can be applied in an effort to optimize maintenance schedules and costs and develop well designs that best balance the costs of well construction with the required well reliability (Xie and Hassanien 2012, Xie et al. 2014).

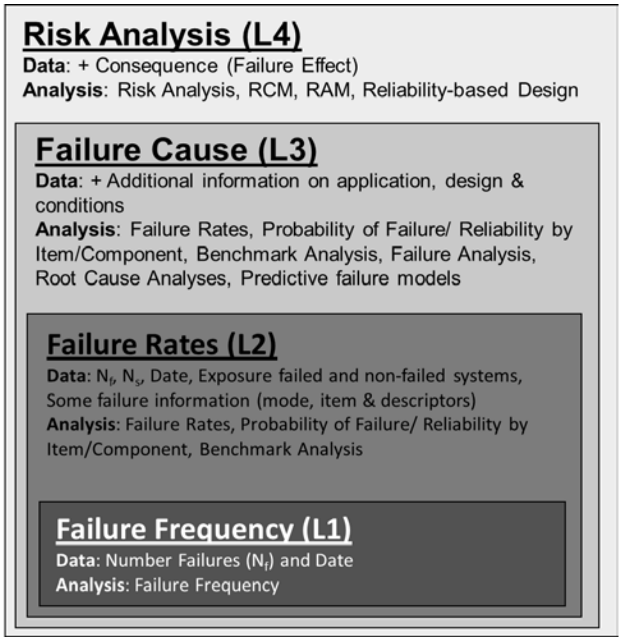


Figure 2: Levels and uses of well reliability data.

As noted above, if well failure probability and consequence data are available, the risk associated with a well failure, *R*, can be estimated using the following:

$$R = P \times C \tag{1}$$

where *P* is the probability of occurrence, and *C* is the consequence of the event and is a measurement of the magnitude of the loss.

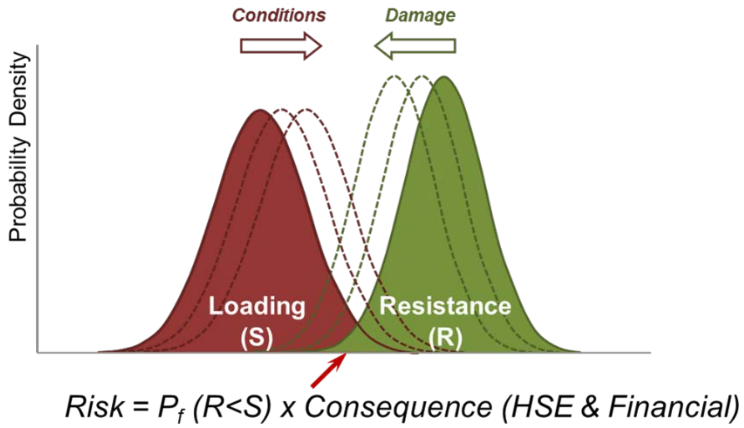


Figure 3: System resistance (capacity), environmental loading (demand) and the probability of failure.

As thermal wells age and are exposed to increasingly more demanding conditions (such as the total number of thermal cycles or increasingly more corrosive fluids), the loading demands on the system increase. In addition, with age and thermal cycle loading, the resistance of the well barriers can be reduced. The result can be an increase in the probability of failure over time, as illustrated in Figure 3 by the increasing overlap between the resistance (capacity) and loading (demand) distribution profiles.

As part of an overall risk management process, as illustrated in Figure 4, these steps typically include: (1) system definition; (2) hazard and failure scenario identification; (3) data collection and estimation of probabilities and consequences of the identified failure events; (4) qualitative risk analysis and, if deemed appropriate and if the data permits, quantitative risk analysis; (5) assessment of the risk (relative to corporate risk criteria or risk matrix); (6) identification of actions to manage and control the estimated risks; and (7) documentation, communication and ongoing repetition and refinement of the process. The motivation and a proposed process for geothermal well integrity, which largely follows the steps of the process shown in Figure 4, was presented by Mansouri (2017) and is shown here in Figure 5. A detailed review of the various risk assessment methods used in the oil and gas and geothermal sectors, the preferred approaches and the differences between the sectors is presented by Lohne et al. (2016, 2017).

Typically, risk assessments conducted on wells have been either qualitative (e.g., subjective relative designations, such as low, moderate and high, for the consequence and likelihood(6)) or semi-quantitative (e.g., orders of magnitude estimates for the consequence and likelihood). Two reasons for this are the lack of sufficient high-quality reliability data required to conduct such quantitative risk assessments and the potential complexity of the risk models. However, even

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[6] For example, the qualitative risk assessments for geothermal wells presented by Summers et al. (1980) and Kalvenes (2017).

relatively high-level reliability data, if available, can be used to support risk-based optimization decisions and activities in the areas of thermal well design, construction, inspection, maintenance, operation and abandonment.

Based on a review of well integrity and risk assessment methods, Lohne et al. (2016) noted that the geothermal industry tends to rely more on qualitative risk assessments than the petroleum industry, likely due to the geothermal sector having less available data, the lack of broad industry reliability data, lack of the use of structured well integrity data tracking systems(7), and the reduced focus on barrier reliability in the geothermal sector compared to the petroleum sector.

5. Thermal Well Reliability Data

As illustrated above, representative well failure and reliability data are generally required(8) to construct a thermal well reliability model, to conduct semi-quantitative or fully-quantitative risk assessments, and to optimize a well design, inspections and interventions in terms of reliability or risk considerations. In this section, a few examples and sources of thermal well failure data are presented with illustrative examples.

5.1 Examples of Well Failure Data for Thermal Oil Recovery Wells

In some of the Western Canadian provinces, oil and gas well Operators are required by the Provincial regulatory bodies to report certain wellbore failure events and associated information. In the Province of Alberta, loss of casing pressure containment above the producing interval and failures of the cement sheath, as evidenced by fluid migration to surface either between the surface and intermediate casing (Surface Casing Vent Flows) or outside of the outermost casing (Gas Migration), must be reported to the Alberta Energy Regulator (AER). This data is available for research purposes from the regulator. In 2012, the database of casing failures was acquired and those failures corresponding to the SAGD and CSS thermal oil recovery projects located in the oil sands regions were identified and extracted. This provided the number of failures per SAGD and CSS recovery project per calendar year.

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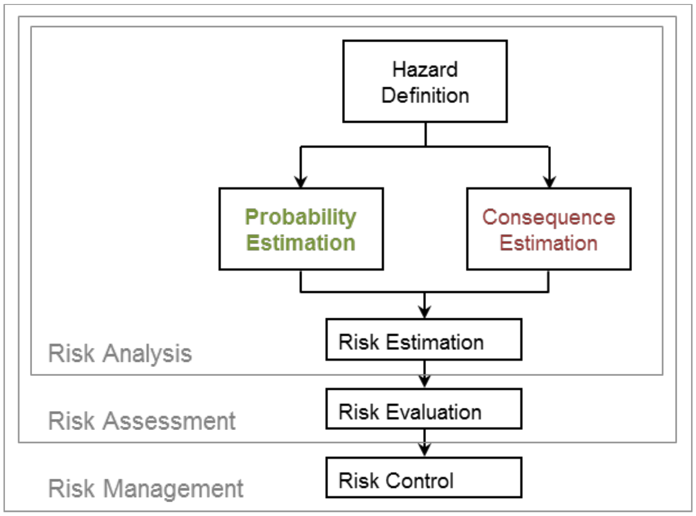
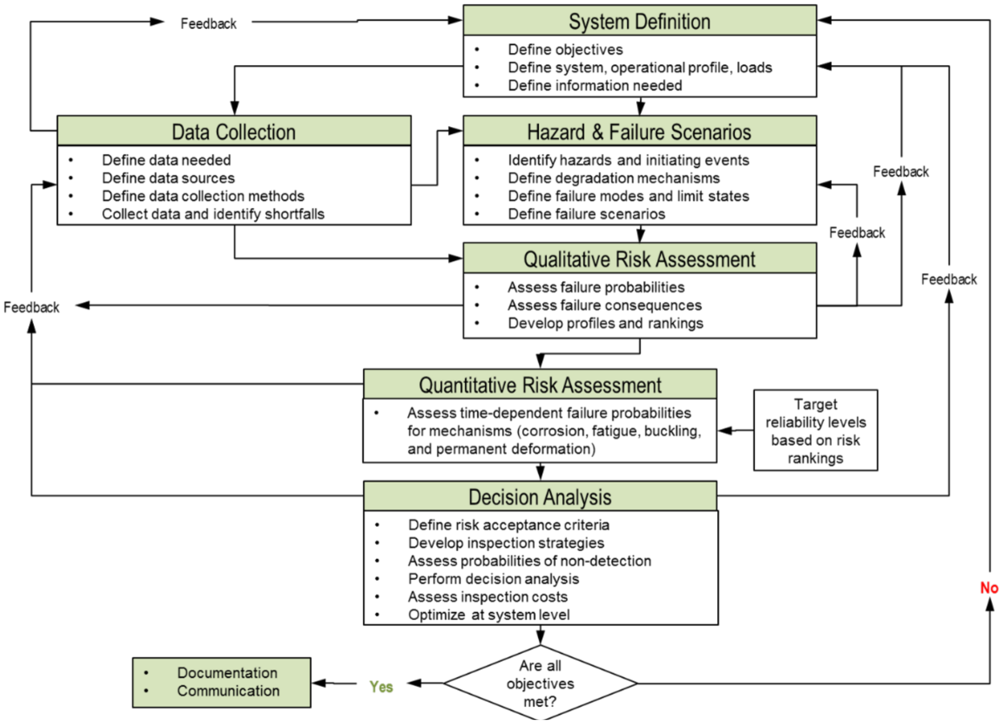
[7] For example, well integrity data management tools and procedures, such as Well Integrity Management Systems (WIMS), are commonly used in the petroleum sector by operating companies. While generally tailored for each company’s specific application, well and data management needs, the WIMS used in the petroleum sector commonly incorporate local regulatory, company and petroleum sector standards, such as NOSOK D-010 (2013). Lohne et al. (2016) and Mansouri (2017) recommended that the geothermal sector consider the adoption of the well barrier approach, structured reliability data systems and quantitative risk assessment methods.

[8] While forms of reliability models may also be constructed based on expert opinion (e.g., qualitative risk assessment models, fuzzy set theory models or Bayesian network models, as noted below in Section 6.3), greater confidence in the predicted outcomes is provided by models supported by field data.



(a) Overall risk management process



(b) Common steps in a risk management process (based on Assakkaf, circa 2004)

Figure 4: Risk assessment and risk management process.

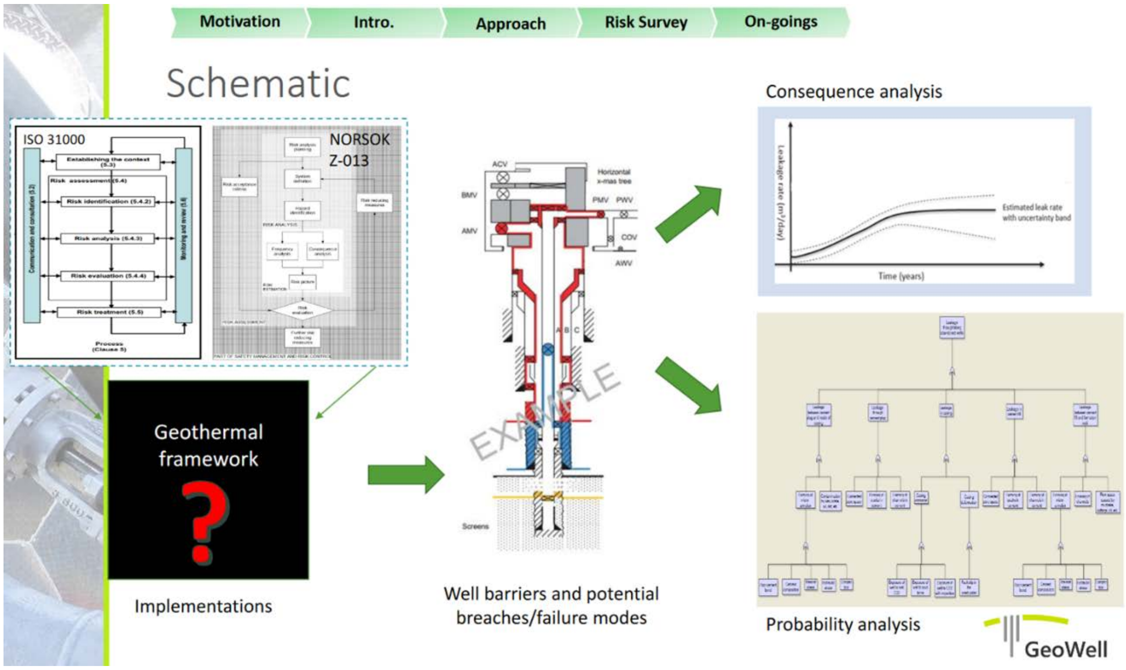


Figure 5: Components of a proposed quantitative risk assessment based approach for geothermal well integrity (Mansouri 2017).

To obtain failure rates, exposure values (i.e., the cumulative number of wells at risk over the period) were obtained from various publications, including annual company reports submitted to the AER, technical papers and operating company information. By taking the ratio of the number of failures to the estimated population at risk each calendar year, estimates of the annual failure rates as a percentage of the producing wells per year were obtained. These failure rate trends are shown for the SAGD and CSS wells in Figure 6. Analysis of the CSS and SAGD thermal oil well reliability data shows that the two main types of casing 'loss of containment' failures tend to be related to shear movement at susceptible formation layers (upper shale layers and at the production formation-to-caprock interface) and near-surface oxidative corrosion (Imperial Oil Ltd. 2012, Hanson 2017, Zahacy 2012). Near-surface corrosion failures account for between 8% and 16% of the CSS and SAGD casing failures in Alberta, with subsurface failures at casing connections(9) and largely attributed to shears at susceptible formations accounting for the majority of the remaining failures (Zahacy 2012, 2015).

These results suggest that, on average, SAGD Operators in the Athabasca oil sands region of Alberta would require an annual reserve inventory of wells of between 1% and 2% to maintain production levels, while CSS Operators in the Cold Lake region of Alberta would require a reserve inventory of between 2% and 3% to maintain production. Industry data has been obtained from the Provincial regulatory body and processed to obtain reliability trends for SAGD and CSS well cement sheath integrity and SAGD sand control systems. Such statistics can be

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[9] About 85% to 95% of oilfield tubular failures, including casing failures, tend to occur at or near casing connections in thermal oil recovery (Imperial Oil Ltd. 2012, Remmer 2013, Zahacy 2012, 2015) and conventional oil and gas wells (Payne and Schwind 1999).

used in project capital budget planning, annual forecasting and, when compared across operations, as a benchmarking metric. The average also serves as a first-level failure model.(10)

It should be noted that review of the literature suggests that, for thermal oil recovery wells, these failure rates are relatively low. For example, in some areas, thermal well damage and failure rates are reported to be as high as 20% and even as high as 100% (Lihong et al. 2013). In order to understand the underlying reasons for such differences in failure rates, much more detailed and high-quality parametric data would be required. Unfortunately, such data is generally not readily available in the thermal well industry, often even within the operating companies themselves (i.e., not without significant investment in data review, standardization, compilation, gap completion and validation).

5.2 Examples of Well Failure Data for Geothermal Wells

As with thermal oil recovery wells, review of the literature shows that there is, unfortunately, very limited information available on geothermal well failure data, information or statistics and reliability measures. A few examples of such data are shown in Figure 7 for geothermal wells in Southeast Asia as presented by Southon (2005) and geothermal wells in Iceland as presented by Lohne et al. (2017).

5.2.1 Geothermal Wells in Southeast Asia

The reliability data presented by Southon (2005) is interesting as it suggests that the completion design and hole size appear to be correlated with the failure rate of the geothermal wells in this application. The failure rate of geothermal wells drilled and completed with ‘big hole’ casing (13.375 inch and 10.75 inch outer diameter, OD, production casing) were about 2.4 to 2.6 times higher than wells drilled and completed with ‘standard holes’ (9.625 inch OD). Larger diameter casing, however, offers larger flow rates and increased energy production compared to the smaller diameter of the ‘standard’ wells. Southon attributed the higher failure rate of the ‘big hole’ wells to the relative weakness of the larger diameter casing and the larger annular region, which may result in poorer cement sheath placement and casing confinement during thermal cycles.

Also, the data presented by Southon indicated that the failure rate of the wells completed using a tie-back completion design was about 2.3 to 2.5 times that of the single-string design. In addition to leaking lapped casing intervals, increased failure rates due to trapped fluids (from trapped free water) and poor cement placement were attributed to this increase rate for wells with the tie-back design. While the tieback completion design has a higher apparent failure rate than the single-string design, Southon noted that the tie-back approach offers the advantage of reduced production casing wear due to drill pipe rotation while drilling the target interval. One question might be, on an overall economic basis and relative to the single-string design, are the potential advantages of the tie-back approach offset by the higher casing failure rate?

This data offer the opportunity to conduct a risked economic optimization between well construction costs, productivity and well reliability and life for the parameters of casing diameter

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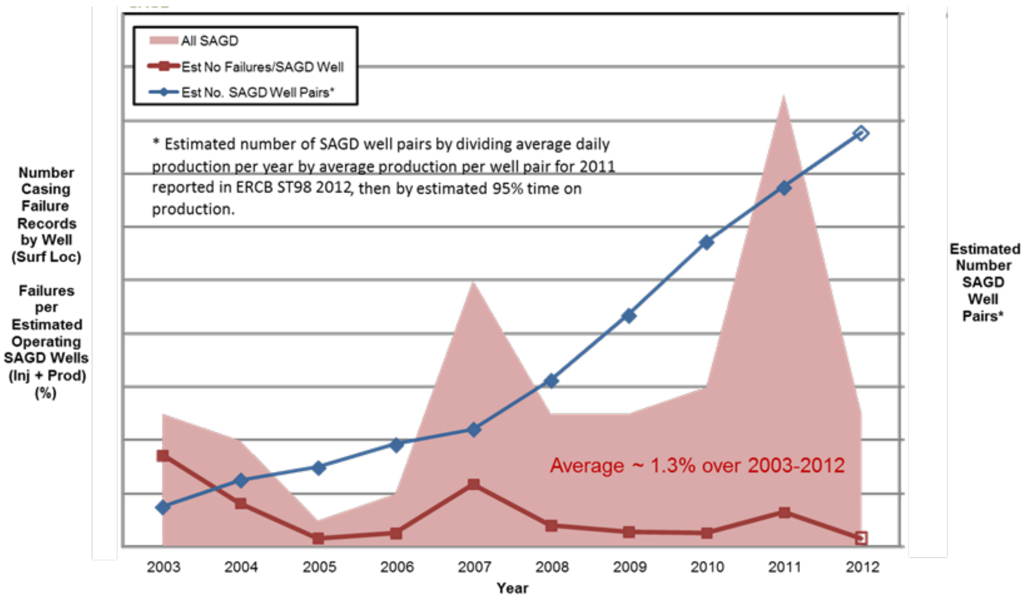
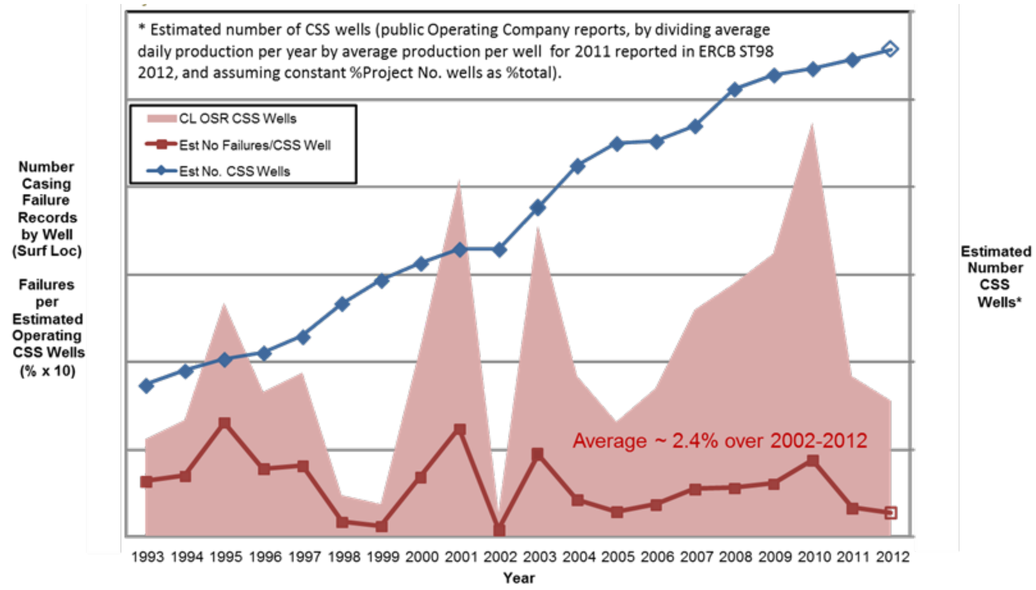
[10] Note that the failure data shown in Figure 6 for SAGD and CSS wells is based on estimates of the number of active production wells per year. Given the uncertainty in the estimates, the number of wells and failures per year were removed. The information shown in Figure 6 is being presented here for research purposes.

and completion type. One could readily envision extending such an economic risk-based model to include other parameters noted by Southon (2005), such as heating rate, SSC temperature susceptibility, well curvature, casing wear, and fluid corrosivity.

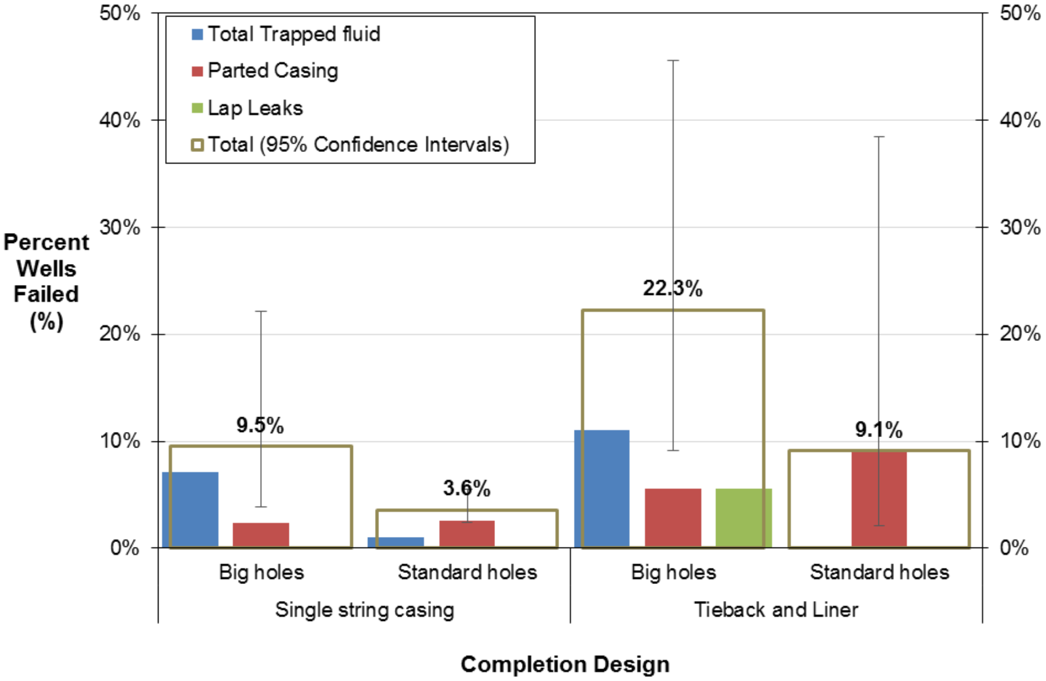


(a) SAGD well failure data with time

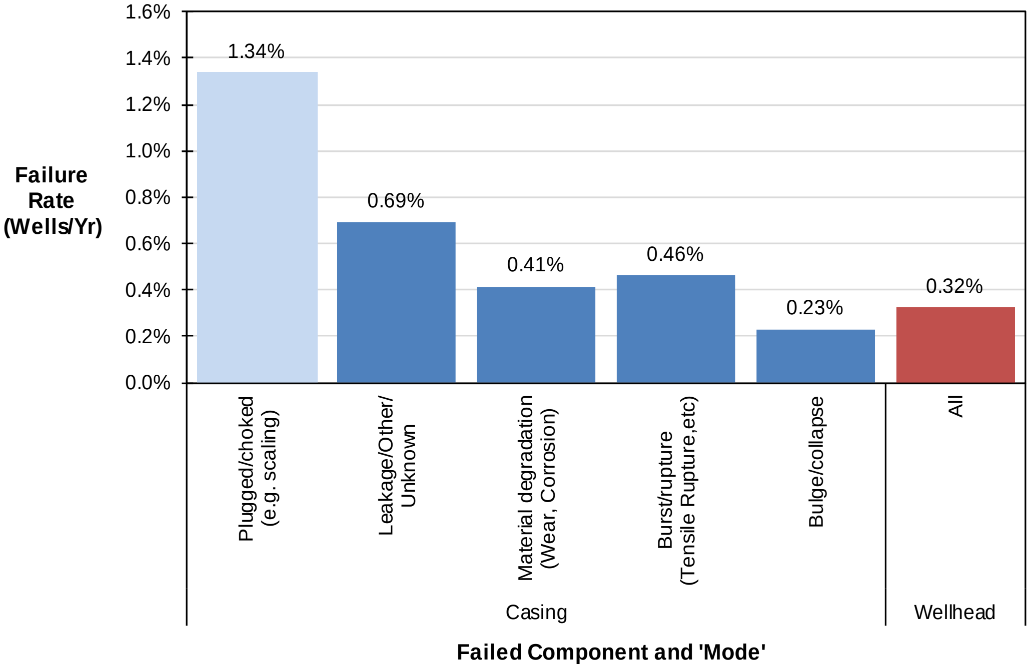


(b) CSS well failure data with time

Figure 6: Example of Western Canadian SAGD and CSS thermal oil recovery well casing failure data (Zahacy 2012).



(a) Southeast Asia geothermal wells (Southon 2005)



(b) Iceland geothermal well failures (Lohne et al 2017)

Figure 7: Examples of geothermal well casing failure data.

5.2.2 Geothermal Wells in Iceland

The reliability statistics presented by Lohne et al. (2017) were based on a subset of 136 identified producing geothermal wells (from a database of 235 total geothermal wells in Iceland, which included production, exploratory, monitoring, and shut-in and abandoned wells), approximately 55% (75) of the wells were identified as 'failed'. With a total estimated exposure of the 136 wells of 2170 well-years, this corresponds to a 'failure rate' of about 0.0346 failures per well-year, or 3.46% wells per year. This identified set of 'failed' wellbores included failures attributed to burst/ruptured, leaking, parted, collapsed/bulged, corroded, and worn casing; plugged/scaled casing; and damaged wellheads, which suggests that the designation of failed wells included loss of containment, loss of access and perhaps also restricted service or loss of target productivity.

Examination of the reliability data presented by Lohne et al. (2017) suggests that the approximate failure rate attributed to loss of casing integrity was approximately 1.8% wells per year (failure rate of 0.018 failures per well-year) with the breakdown of this being about 0.69%/yr to leakage; 0.41%/yr to material degradation (corrosion/wear); 0.46%/yr to burst/rupture; and 0.23%/yr to bulge/collapse.

Thorhallsson (2003) noted that one of the primary reasons geothermal wells in Iceland are taken out of service is because of casing damage and failures, and one of the primary factors of such damage are the loads introduced by temperature reductions during operational related thermal cycles. Thorhallsson (2003) noted that reducing such thermal-cycle loading (due to shutting-in wells, killing wells and cool-down during workovers) has been associated with improved geothermal well longevity. As with thermal oil recovery wells, Thorhallsson (2003) noted that, in addition to thermal-cycle induced casing failures, one of the other dominant mechanisms for casing damage and failure is near-surface oxidative corrosion. The factors (high temperature, access to water in the near-surface region and well age), as well as the inspection and repair methods used (excavation and external repairs or replacement), are similar to those used in thermal oil recovery applications (Zahacy 2015, Hanson 2017).

These failure statistics suggest that loss of casing containment accounts for a significant portion of the failure rate of the geothermal wells in Iceland. Additional investigation into this data set, such as in an effort to identify influential factors (e.g., casing connection design, material grade, well age, number of thermal cycles, fluid corrosivity), should be considered.

5.2.3 Other Reliability Data and Failure Statistics

Other limited indications of geothermal well reliability and failure statistics include:

- *The Geysers field, California in 1998*: 50 wells identified with casing deformation in the then Unocal portion of the field (Allan and Philippacopoulos 1998) with reduced casing diameter and 'doglegs' resulting in reduced production and potential abandonment. Based on information presented by Williamson (1999), about 380 wells were estimated in The Geysers field at that time, which suggests a failure frequency of about 13%.
- *Molasse Basin, Germany*: about 40 successful deep geothermal wells from circa 2005 to 2015 (10 yrs) with 4 casing 'failures' or 10%, including three Trapped Annular Pressure

(TAP) collapses plus one ‘tectonic collapse’ (Lentsch et al. 2015). If all 40 wells had 10 years of exposure time(11), the failure rate would be 1% wells/yr.

Geothermal well barrier failure data was sought from geothermal well Operators and regional regulatory bodies in mature regions, including New Zealand and California. Unfortunately, responses to inquiries were either not received or, in the case of California, the Regulator noted that failure data for geothermal wells was largely not available through the Regulator, in part because, unlike State statutes for oil and gas wells, there were no similar statutory reporting requirements for geothermal wells on private or State lands (Truschel 2018).

5.2.4 Observations and Recommendations

The above limited data suggests that, in many cases, the failure rates of geothermal wells appear to be higher than some of the thermal oil recovery wells (e.g., the SAGD and CSS wells in Western Canada), but in other cases of similar magnitude or lower. Without additional information, common failure data or metrics, interpretation of the extraction of insights regarding possible underlying reasons for such differences cannot be made.

Geothermal well Operators are encouraged to consider developing standard well integrity and failure information tracking systems.(12) If such data sets, failure nomenclature and information tracking systems were to be standardized across Operators (common data sets and terminology)(13), geothermal well Operators could readily share data and metrics, have confidence in the data, develop improved predictive wellbore failure and reliability models, and realize many of the benefits associated with the use of well reliability data, such as improved well availability, optimized well inventories and reduced well inspection and repair costs, as noted above.

6. Reliability and Risk-ranking Models

From a completion standpoint (i.e., neglecting equipment, such as pumping systems and tubulars, within a well), thermal wellbore availability is closely related to the reliability and integrity of the primary structural and fluid containment barriers. Wellbore damage models may be developed based on data (empirical models), on the physics of the damage mechanism (mechanistic) or on some combination of the two. While data-driven models might be the easiest to develop, to create reliable models, large sets of data are typically required and the resulting models (correlations) are largely limited to the applications and conditions on which the data was obtained, making the application of the models to new applications highly questionable.

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[11] The exposure time of all of the wells is likely less than this.

[12] Such systems may be based on data structures, standards and terminology developed for the oil and gas industry, such as NORSOK D-010 (Standard Norge 2013), ISO 16530-1:2017 (ISO 2017), ISO 31000:2018 (ISO 2018) and ISO 14224:2016 (ISO 2016). The benefits of geothermal well integrity standardization were recognized by the Geothermal Resource Council, as noted by Spielman (2004).

[13] Such data systems may be more readily established early in the life of a geothermal project during the early planning and design stage, such as in a new EGS project, than in a mature project with large volumes of disperse data in multiple data formats (electronic and paper files).

Conversely, models based on the underlying mechanisms can be very complex, often including many more parameters than can be evaluated based on available field data, necessitating sizable efforts and investment into lab- and simulation-supported validation. However, once validated, such models can typically be extended more broadly with greater confidence in the accuracy of the predictions.

The lack of downhole wellbore reliability data typically drives those attempting to develop reliability or risk models to work with higher-level field or industry failure rates (overall averages) or to develop relatively simple, empirical models.

A relatively simple but highly adaptable reliability model can be developed based on the application of Bayes' rule (Mendenhall and Sincich 1988) to estimate the failure rate of a member in a population. For an identified parameter, *A*, which influences the damage mechanism and failure rate, the modified failure rate, $r(f|A=a)$, of the wells which have the attribute value of the parameter corresponding to $A=a$ can be estimated by modifying the overall average failure rate, $r(f)$, by the percentage of the population that failed with $A=a$:

$$r(f|A=a)=\frac{p(A=a|f)}{p(A=a)}r(f) \qquad (2)$$

That is, where $p(A = a \mid f)$, the proportion of failures that occur when A = a and $p(A = a)$ is the proportion of the population with $A = a$. It is apparent that the failure rate weighting factors would have values above or below one, depending on if the attribute value $A=a$ has a positive or negative effect on the probability of damage and failure. Similar failure rate adjustment factors can be developed for a number of identified attributes of the wells. For example, for the thermal well casing failures (e.g., due to a specific mechanism, such as shear or tensile parting), identified influential attributes might include casing diameter, casing connection type, casing material grade, presence of weak formations, quality of the cement sheath placement, peak temperature and the number of thermal cycles. Cross-correlation of these influential parameters may also be taken into account.

6.1 Thermal Oil Recovery Well Risk-ranking Models

The influence of key parameters and their impact on the resulting failure rate (and reliability) of the thermal wells could be developed based on analysis of field data, analysis of data from analog fields, numeric simulation results, laboratory testing or engineering judgement. As the quality of the information improves (volume, accuracy and completeness of the data), such as with experience or focused efforts to collect data on identified influential factors, the values of the overall failure rate and weighting factors can be reviewed and updated, which would in turn tend to improve the predictive nature of the model.

This type of model was developed for one SAGD Operator in Western Canada. The model provides the well and asset integrity personnel in the company with an estimate of the probability of failure of the various wells in their inventory based on the environmental, well design and operational attributes of the well (Figure 1). The model also provides insights related to the consequence of damage and well failures. The Operator uses their corporate risk matrix to determine the relative risk of the wells based on the estimated probability and consequence (Equation 1) for a set of identified subsurface and surface casing, sand control, cement sheath and wellhead failure types. The well and asset integrity personnel consider the risk model results in allocating well monitoring, inspection and repair resources. As the Operator's available information and understanding evolve, so too will their wellbore risk-ranking model.

6.2 Example of Well Risk-ranking Model for Geothermal Wells

Similar wellbore risk-ranking models could readily be developed for geothermal wells by following the core steps used to develop such models for thermal oil recovery wells. For example, using the approach described by Equation 2, a two-parameter casing damage/failure model could be developed for the geothermal wells in the Southeast Asia application noted by Southon (2005), where the parameters would be casing size (big hole and standard) and completion type (single-string casing and tie-back and liner).

$$r(f|Southon\ data) = F_{Casing} \cdot F_{Completion} \cdot r(f) \tag{3}$$

For the data presented by Southon (2005), the failure rate multipliers to the overall population failure rate of 4.6% wells would be about 2.9 and 0.81 for 'big hole' and 'standard' casing, respectively, and 0.87 and 3.7 for single-string casing and tie-back and liner completion designs, respectively. The model tends to be biased by the distribution and clustering of the data toward portions of the data that comprise more of the record set. Figure 8 shows the predicted versus actual failure rates from this model.

Figure 8 shows that the failure prediction or 'risk-ranking' model for the Southon geothermal well data tends to be somewhat conservative for tie-back completions and 'big hole' casing diameters compared with the single-string standard hole design, which biases the model due to the dominance of this data in the set (accounting for 89% of the records). The value of such a model can be illustrated by considering a scenario where there were no standard hole tie-back and liner completion failures, in which case the model would have predicted about 11.4% failures, compared with the observed 9.1% (one failure). Such a relatively simple and conservative model is useful for risk-ranking purposes, and it can be readily updated as additional data is acquired and modified as other influential parameters are identified.

6.3 Other Potential Forms of Well Risk-ranking Models

As noted above, other forms of reliability and risk-ranking prediction models may also be developed for wells, such as forms which have been applied in other areas of the energy industry, including pipeline integrity, blowout risk assessment, field development option identification, and artificial lift failure prediction. Forms of these models include those based on expert opinion, such as fuzzy set theory models (Irani and Hamuli 2016); data-focused models, such as multivariable correlation and neural-network models (Liu and Patel 2013, Schuetter et al. 2015); and forms such as Bayesian network models, which may be well suited to sparse data sets with consideration of other sources of information, such as expert opinion and lab-based, industry or analog data (Mah et al. 2014, Whitfield 2016, Koduru and Lu 2016).

7. Conclusions

The following are observations, conclusions and recommendations developed based on the material presented in this paper:

- Significant potential economic and asset integrity benefits can be gained from improved geothermal well reliability data tracking systems, standardization and the development of failure and risk-based models. The drilling challenges and high relative costs associated with geothermal wells (in comparison to oil and gas wells of comparable depths) are strong motivators for advancing geothermal well reliability and failure data, common data structures, and improved well barrier damage and failure prediction models.
- As a first step, even relatively high-level wellbore reliability data can be used to predict future failures, improve projections and forecasts, improve designs, and develop models for risk identification and risk-ranking of wells.
- Examples of thermal oil recovery and geothermal well failure data illustrates some of the key differences between application conditions and well designs. Additional detailed, high-quality data is required to understand the basis of the differences and identify opportunities for improvements to well design, implementation and operation practices.
- A relatively simple but highly flexible and adaptable reliability model was presented. Such a model was developed for a SAGD thermal Operator and similar models may be developed for Operators of geothermal wells.

For the thermal oil recovery and geothermal energy sectors to accelerate the evolution of the use of field data, recognize the benefits of the digital transformation through increased well reliability and availability, and advance their competitive position relative to other energy suppliers, increased focus on high quality well reliability data and improved predictive damage and asset integrity models should be pursued.

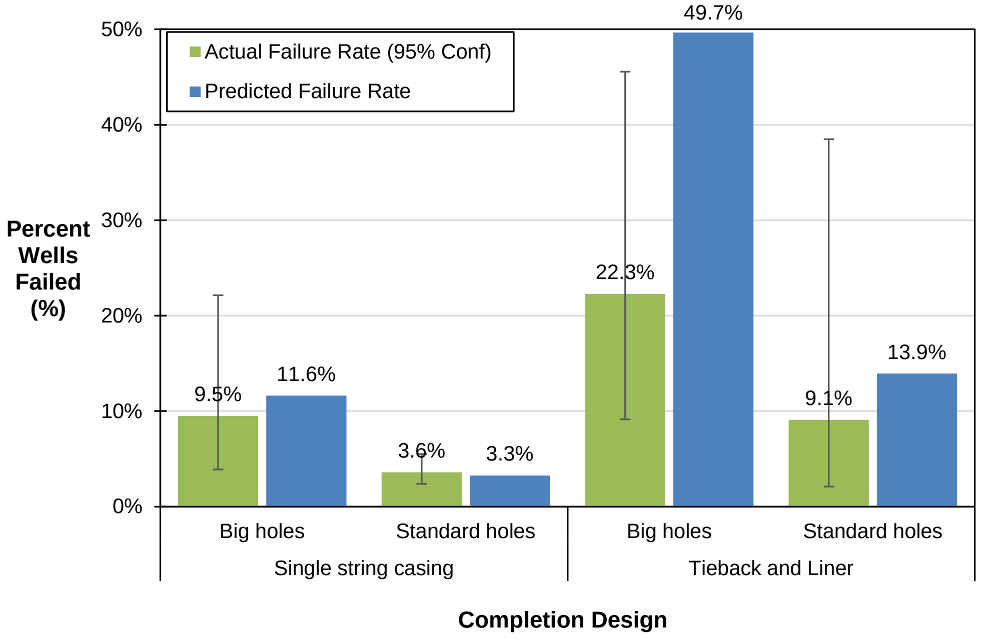

Figure 8: Comparison of the actual and predicted failure rates for the data presented by Southon (2005) using the first-level failure model approach of Equation (3).

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