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Engineering Management and Inspection Schedule of Petroleum Well Integrity

Musaed N. J. AlAwad[1] and Hawwas A. Mohammad[1,2]
[1]King Saud University, College of Engineering,
Petroleum and Natural Gas Engineering Department, Riyadh, Saudi Arabia
[2]King Abdulaziz City for Science and Technology,
Riyadh, Saudi Arabia.
Corresponding Author: **Musaed N. J. AlAwad**

Abstract

Oil and gas supply the world with energy by approximately 60% of all available energy sources. The global hydrocarbon well inventory accounts for at least 1.8 million wells, more than 870,000 wells of these wells are active. Wells must be designed to ensure well integrity, i.e. that the fluids stay contained within the wellbore, and that the surrounding subsurface layers, including aquifers, are protected. Well integrity is a result of technical, operational and organizational barriers applied, with the intention to contain and control the reservoir fluid and well pressures. Failure to obtain and maintain adequate well integrity (barriers) could lead to catastrophic events, like demonstrated in the Gulf of Mexico in 2010, with the Deepwater Horizon incident. Well integrity failures hit a company hard at every level. Hydrocarbon production is affected, individuals may be hurt and environmental disaster is a potential risk. Therefore, well integrity can be defined as the sustainability of the equipment to operate safely for the full design life. For an oil/gas well to maintain its integrity and be produced effectively and economically, it is pertinent that a complete zonal isolation is achieved through out the life of the well. This complete zonal isolation, however, can be compromised due to factors that come into play during the operative life of the completed well. In this study, the typical well integrity primary and secondary barriers are outlined in details. Examples of Worldwide incidents due to well integrity failure are presented. An appreciable statistical data on well integrity failures worldwide are presented and analyzed. Furthermore, risks associated with different types of well integrity failure issues and how to reduce/mitigate them are discussed. Procedures, roles and responsibilities of personnel involved in the well lifecycle towards well integrity are presented. Finally, a holistic Well Integrity Barriers Inspection Schedule for use by the oil and gas producing companies worldwide are developed. This paper provides the oil industry society with a clear picture on the elements of petroleum well integrity; a general well integrity inspection schedule; and a risk based inspection and maintenance matrix.

Keywords: well integrity management (WIM), well barriers (WBs), well barrier element (WBE), well barrier failure frequency, Well Integrity Inspection Schedule

INTRODUCTION

Well integrity problems are seriously facing the oil and gas industry worldwide. For example, 45%, 34%, and 18% of the wells in Gulf of Mexico, North Sea UK, and North Sea Norway, respectively are suffering from well integrity failures (Decoworld, 2014).

According to the Society of Petroleum Engineers (SPE, 2016), over the next decade, the oil industry will drill more wells than they have in the last 100 years and that of the world's current inventory of 1.8 million wells, roughly 35 percent have integrity problems (Viable opposition, 2013). In the Middle East, over 50% of all wells have integrity issues with 10-15% of these being critical (Well Integrity Conference, 2015). Furthermore, the rise in extended reach wells and other high risk characteristics, such as HP/HT wells, shale formations, corrosion, scale, and sour service fields in the Middle East, are increasing the spotlight on well integrity.

The most common definitions of “well integrity” are based on the concept of constantly retaining two intact barriers between the reservoir and the external environment. The NORSOK D-010, 2004standard, developed by the Norwegian petroleum industry, provides the following definitions:

a) Well Integrity: “Application of Technical, Operational and Organizational Solutions to Reduce Risk of Uncontrolled Release of Formation Fluids throughout the Life Cycle of a Well”.
b) Well Barrier: “Envelope of one or several dependent barrier elements preventing fluids or gases from flowing unintentionally from the formation, into another formation or to surface”.
c) Well Barrier Element (WBE): “An object that

> alone cannot prevent flow from one side to the other side of itself".

Well integrity management is an art of managing the well to reduce risk applying technical, operational and organizational solutions (Sanjiv, 2014), and it is divided into four distinct stages (See Figure 1): well design stage, well construction stage, well integrity monitoring (production) stage, and well abandonment stage [James, 2011].

Well integrity problems occur because of a wide range of circumstances. Many different types of failures can lead to loss of well integrity with varying degree of severity. For any of the worldwide occurred blowouts (see Table 1), a long chain of events led to the incidents. The simplest approach would be to consider failure of individual well components. When a barrier failure occurs, an assessment will establish the magnitude of the health and environmental risk posed by the leak so that the repairs can be scheduled appropriately.

The obvious consequences of loss of well integrity are blowouts or leaks that can cause material damage, personnel injuries, loss of production and environmental damages resulting in costly and risky repairs

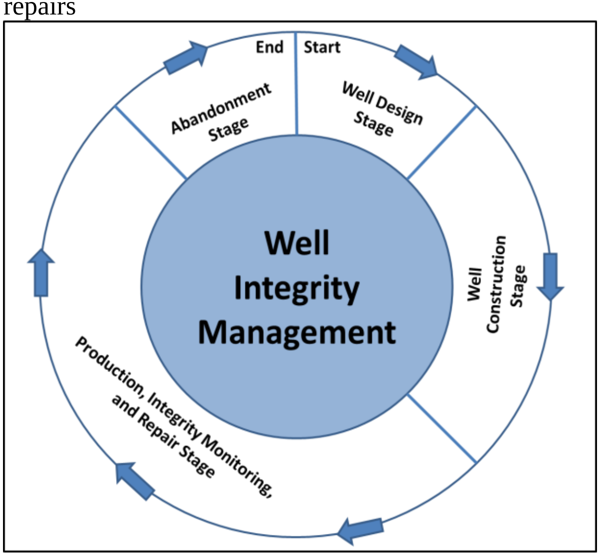

Figure 1 Stages of Well Integrity Management (James, 2014)

Table 1 Summary of well integrity incidents (Dickson, 2013)

Year	Well Integrity Incident	Region	Number of Fatalities	Causes
1901	Gusher at Spindletop	Texas, U.S.A	Nil	Mining Engineers were mining not knowing there was oil reserve there.
1969	Santa Barbara oil spill	Southern California, U.S.A	Nil	Ruptured underwater pipe
1977	Ekofisk Bravo blowout	North sea, Norway	Nil	(DHSV) was not properly locked in during the work-over operation
1989	Sega Petroleum's underground blowout	North sea, Norway	Nil	There was a case of casing burst in the well
2004	Statoil's incident on Snorre A	North sea, Norway	Nil	Gas leaked through damaged casing
2010	BP's Macondo blowout	Gulf of Mexico	11	Cement was not allowed to dry before running negative pressure Test
2012	Chevron oil fire	Niger Delta, Nigeria	2	Failed Blowout Preventer

A study conducted by PSA, 2006, clearly the production tubing is the dominating component with failure. This is not unexpected as the tubing is exposed to corrosive elements from the produced fluids and, the production tubing consists of many threaded connections where the high number of connections gives a high risk of leak. Two well barriers between the reservoirs and the environment are required in the production of hydrocarbons to prevent loss of containment. If one of the elements shown in Figure 2 fails, the well has reduced integrity and operations have to take place to replace or restore the failed barrier element(Hans-Emil, 2012)

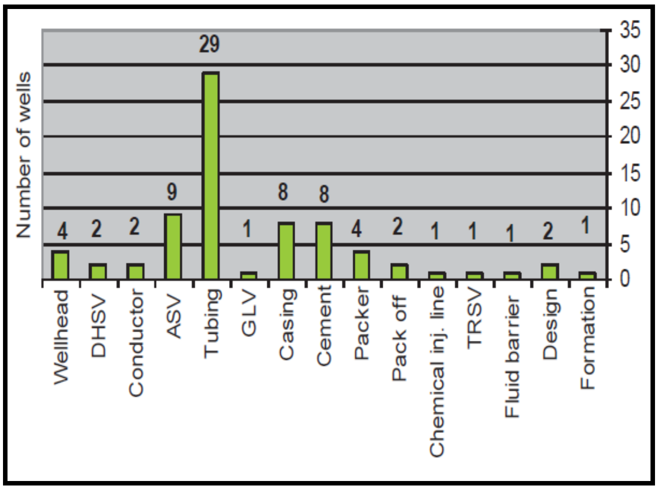

Figure 2 Examples of barriers elements failure (PSA, 2006)

To further illustrate what can go wrong in wells, data from offshore operations in the Gulf of Mexico spanning 1992 to 2006 clearly demonstrates the significant role cement barriers play in ensuring safe and productive operations during the drilling and completion phase of a well (Izon, 2007). As shown in Figure 3, cementing failure contributed to over 50% of the well control incidents recorded (Izon, 2007).

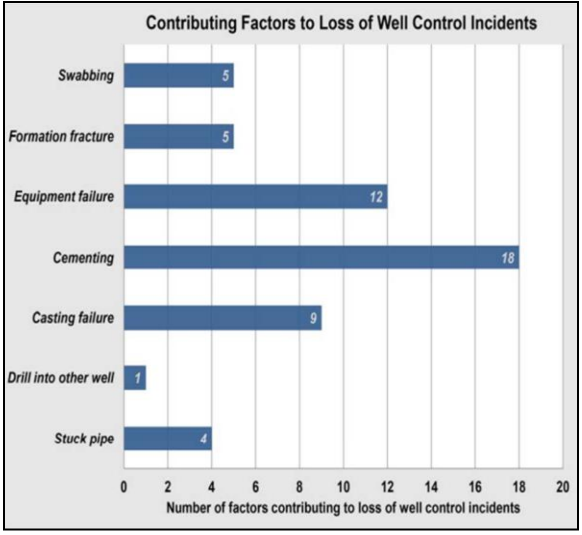

Figure 3: Contributing factors to loss of well control incidents in the Gulf of Mexico (Izon, 2007).

Vignes and Aadnoy (Vignes, 2010) examined 406 wells at 12 Norwegian offshore facilities operated by seven companies. Their dataset included producing and injection wells, but not plugged and abandoned wells. Of the 406 wells they examined, 75 (18%) had well barrier issues. There were 15 different types of barrier that failed, many of them mechanical (Figure 4), including the annulus safety valve, casing, cement and wellhead. Issues with cement accounted for 11% of the failures, whilst issues with tubing accounted for 39% of failures.

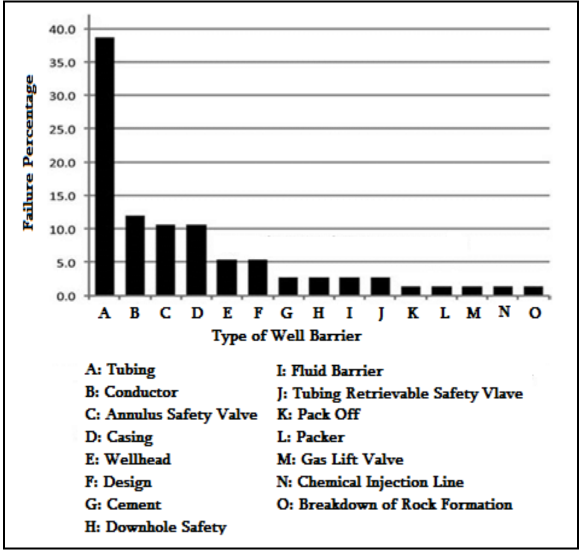

Figure 4 Example of barrier element failures (Vignes, 2010).

Well integrity, as defined by NORSOK standard, depends not only on equipment robustness, but on the total process, the competence and resources of the organization and the competence of the individual. This study describes efficiently well integrity management throughout the life cycle of a well with a particular focus on typical well barrier elements that are important in the operational phase and permanent plug and abandonment phase.

OBJECTIVES OF THE STUDY

The objectives of this study are the following:

i) Extensively review and analyze well integrity case studies worldwide in order to:
  - Understand the concept of well integrity and the corresponding regional standards and regulations.
  - Understand the different stages from well operations, design and construction, to production and its impact on well integrity.
  - Identify risks associated with different types of well integrity failure issues and how to reduce/mitigate them.
  - Define procedures, roles and responsibilities of personnel involved in the well lifecycle towards well integrity.

ii) Develop a universal “Well Integrity Barriers Inspection Schedule” for use by the oil and gas producing companies in the Arabian Gulf and worldwide.

METHODLOGY

A comprehensive search was conducted to compile a worldwide well integrity statistical data based on the type of barrier failure with age. Data collections were collected through several regional publications, journals, reports, conference proceedings and corporate web sites of interest. The summary of findings from published statistics on well barrier and well integrity failure are presented at Hawwas, 2015. In this study wells are categorized into seven groups based on their barrier failure frequency with age as shown in Table 2.

Table 2 Well Integrity Problems Classification Criterion

Group	Well Age Range, years
A	0-4
B	5-9
C	10-14
D	15-19
E	20-24
F	25-29
G	≥30

Classification criterion shown in Table 2 is used to analyze well integrity failures using the survey of the literature available data performed in this study. The statistical data of well barriers failure frequency with age was excluded wells with unknown age (see Hawwas, 2015).

RESULT AND DISCUSSION

As shown in Table 3, it is difficult to come up with a mathematical model for well integrity failure likelihood. Most well integrity failure modes can occur anytime in the well life. However, magnitude of well integrity failure due to specific barrier can be predicted as shown in Figure 5. Well integrity barriers failure occurring frequency based on the data collected in this study are as follows:

i) Cement failure (12446 incidences).
ii) Casing failure (2421 incidences).
iii) Production tubing failure (643 incidences).
iv) Formation failure (109 incidences).
v) Wellhead failure (78 incidences).
vi) Other barriers (Minor indecencies).

Table 3: Summary of Failure Frequency of Individual Well Components with Age (Part 1)

Problem	Well Age groups, years							Total Wells	Source
	A 0-4	B 5-9	C 10-14	D 15-19	E 20-24	F 25-30	G ≥30		
Wellhead	-	2	-	2	-	-	-	78	Vignes B. and AadnøyB.S, 2010
	-	-	-	-	-	74	-		Calosa W.J. and Sadarta B., 2010
SSSV	1	1	-	-	-	-	-	3	Vignes B. and AadnøyB.S, 2010
	-	1	-	-	-	-	-		Dickson UdofiaEtetim,2013
Conductor Pipe	1	-	-	-	1	-	-	2	Vignes B. and AadnøyB.S, 2010
ASV	6	3	-	-	-	-	-	9	Vignes B. and AadnøyB.S, 2010
Production tubing	4	15	5	5	-	-	-	643	Vignes B. and AadnøyB.S, 2010
	-	-	-	-	-	-	614		Davies et al., 2014
GLV	-	1	-	-	-	-	-	1	Vignes B. and AadnøyB.S, 2010
Casing	320	-	-	-	-	-	-	2421	Ingraffea, 2012
	91	-	-	1118	-	-	-		Davies et al., 2014
	4	2	-	1	-	1	-		Vignes B. and AadnøyB.S, 2010
	1	-	1	-	-	-	-		Dickson UdofiaEtetim,2013
	-	-	11	-	-	-	-		Yuan, 2013
	-	-	-	-	1052	-	-		Ingraffea, 2012
	-	-	-	-	-	7	-		Calosa W.J. and Sadarta B., 2010
	-	-	-	-	-	-	74		Vignes, 2011
	-	-	-	-	-	-	98		Sivakumar and Janahi, 2004
Cement	3	1	4	-	-	-	-	12446	Vignes B. and AadnøyB.S, 2010
	1	-	-	-	-	-	-		Dickson UdofiaEtetim,2013
	-	-	-	-	-	-	37		Chillingar and Endres, 2005
	-	220	-	-	-	-	-		Davies et al., 2014
	-	-	-	-	424	-	-		Marlow, 1989
	-	-	-	-	-	44	-		Calosa W.J. and Sadarta B., 2010
	-	-	-	-	-	-	503		Davies et al., 2014
	-	-	-	-	-	-	14556		Watson and Bachu, 2009
	-	-	-	-	-	-	10153		Claudio Brufatto et al., 2003
Packer	2	-	2	-	-	-	-	4	Vignes B. and AadnøyB.S, 2010
Packoff	-	-	1	-	-	1	-	2	Vignes B. and AadnøyB.S, 2010
CIL	1	-	-	-	-	-	-	1	Vignes B. and AadnøyB.S, 2010
TRSV	-	1	-	-	-	-	-	1	Vignes B. and AadnøyB.S, 2010
Fluid barrier	-	1	-	-	-	-	-	1	Vignes B. and AadnøyB.S, 2010
Design	1	-	1	-	-	-	-	2	Vignes B. and AadnøyB.S, 2010
Formation	1	-	-	-	-	-	-	109	Vignes B. and AadnøyB.S, 2010
	-	-	-	-	-	108	-		Calosa W.J. and Sadarta B., 2010

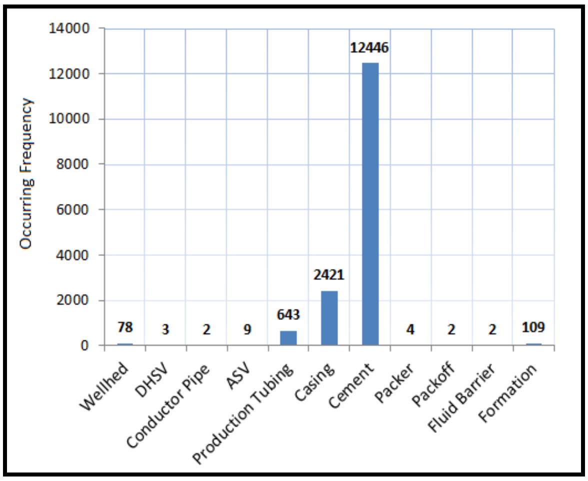

Figure 5: Well Integrity Barriers Failure Occurring Frequency

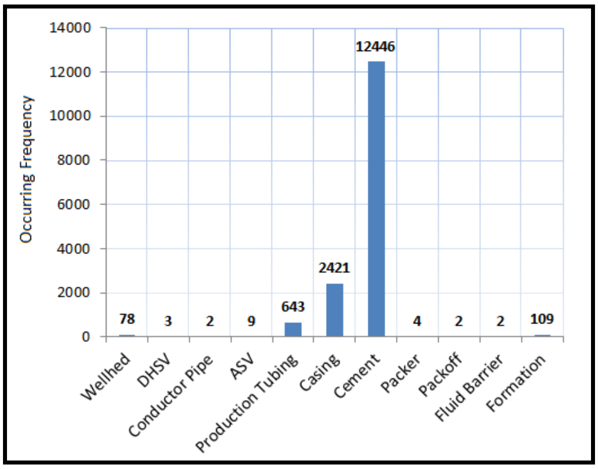

Figure 5: Well Integrity Barriers Failure Occurring Frequency

Well Integrity Barriers Inspection Schedule

It is clear that all of these barriers, except formation, are controllable and can be well selected based on the reservoir conditions.

In order to develop a well integrity barriers inspection schedule, barriers failure rates and severity criteria are defined in Table 4. It is necessary to review the entire well stock in the field and develop a holistic inspection schedule. Some of the wells, including already abandoned wells, can pose risks that are not visible under normal scrutiny. The required information in an oil field includes (Wildwell, 2015):Well Stock, Well Design, Well Records, Surveillance, Compliance, Company well integrity systems, Regulatory.

A holistic well integrity inspection schedule will be developed based on the statistical data presented earlier in this study. Off course, each geographical area may differ from another, but the well design/construction criteria remain almost the same with minor difference in some cases.

Data tabulated in Table 3 is used to produce Figure 5. It is clear that the most critical well barriers are the cement, casing, production tubing, wellhead, and formation. Off course all the remaining barriers suffer from some kind of failure as well. Based on information presented earlier (data tabulated in Hawwas, 2015, and criteria shown in Tables 2 and 3) a holistic well integrity inspection schedule is developed and presented in Table 5.

Risk Analysis of Well Integrity Barriers Failure

Rates of well integrity failure can be divided into four categories as follows:

A) ***Remote Failures*** within 20 years or more.
B) ***Occasional Failures*** within 4 to 5 years.
C) ***Likely Failures*** within 2 to 3 years.
D) ***Frequent Failures*** within 1 year or less.

Severity of well integrity failures are divided into four categories as follows:

I) ***Catastrophic Failures*** where major system damage, system loss, death or permanent disability.
II) ***Critical Failures*** where the failure will degrade the system beyond acceptable limits, so that deaths or injuries may occur if no further action is taken (assuming there is time available to do so).
III) ***Major Failures*** where the failure will degrade the system beyond acceptable limits, but adequate countermeasures are available to control the possible unwanted effects of the failure.
IV) ***Minor Failures*** where the failure does not degrade the overall performance beyond acceptable limits.

Based on the above classification of well integrity failures rates and severity, well integrity failure risk analysis matrix can be generated as shown in Table 4. For easier recognition of the risk magnitude, color coding is normally used as shown in Table 4. Below is the description of the risk color code [Norwegian Guidelines for Well Integrity, 2011]:

i) ***Red Color*** represents extremely high hazard (EHH). In this category, one barrier failure and the other is degraded/not verified, or leak to surface. A well categorized as Red should be regarded to have an associated risk which is considerably higher than the risk associated with an identical new well with design in compliance with all regulations. Typically a well categorized as Red will be outside the regulations. Repairs and/or mitigations will be required before the well can be put into normal operation and there will usually be an immediate and urgent need for action.

ii) ***Pink Color*** represents high hazard (HH).In this category, one barrier failure and the other is intact, or a single failure may lead to leak to surface. A well categorized as Orange should be regarded to have an associated risk which is higher than the risk associated with an identical new well with design in compliance with all regulations. Typically a well categorized as Orange will be outside the regulations. Repairs and/or mitigations will be required before the well can be put into normal operation, but the well will still have an intact barrier and there will usually not be an immediate and urgent need for action.

iii) ***Yalow Color*** represents medium hazard (MH).In this category, one barrier degraded, the other is intact. A well categorized as Yellow should be regarded to have an incremental associated risk which is not negligible compared to the risk associated with an identical new well with design in compliance with all regulations. Although a well categorized as Yellow has an increased risk, its condition is within regulations.

iv) ***Green Color*** represents low hazard (LH). This category represents a healthy well - no or minor issue. A well categorized as Green should be regarded to have an associated risk which is identical or comparable to the risk associated with an identical new well with a design in compliance with all regulations. It does not necessarily mean that the well has a history without failures or leaks, but the well is in full compliance with the double barrier requirement.

Table 4 Well Integrity Failure Risk Analysis Matrix (AICC, 2015)

Hazard Severity		**Hazard Probability**			
		D. Frequent	**C. Likely**	**B. Occasional**	**D. Remote**
I.	**Catastrophic**	EHH	EHH	HH	HH
II.	**Critical**	EHH	HH	HH	MH
III.	**Major**	HH	MH	MH	LH
IV.	**Minor**	MH	LH	LH	LH

Well Integrity Barriers Failure Rate Tending

Tending of failure rate against time can help to determine inspection frequencies for certain equipment and influence future replacement and selection. The expected well components failure rate across time are divided into three categories (see Figure 6) as follows:

i) Early life (decreasing failure rate), when failure is attributed to components quality.
ii) Useful life (constant failure rate), when failure is due to normal service stresses.
iii) Wear out (increasing failure rate), when failure is due to wear and tear.

Holistic Well Integrity Inspection Schedule

Based on the analysis presented above, Table 6 is generated. Data presented in Table 3 is used to produce Figure 7. Table 5 and Figure 7 provided a holistic well integrity inspection schedule.

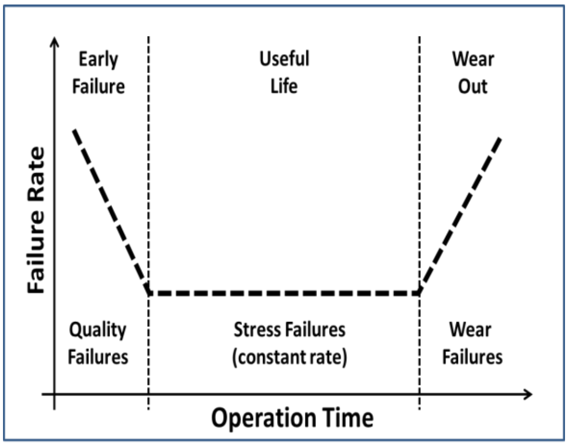

Figure 6: Well Components Failure as a Function of Time (OGP Draft 116530-2, 2012)

Table 5: A Holistic Well Integrity Inspection Schedule (part-1)

Well Barrier Type	Inspection Frequency	Failure Effect Severity	Potential Problems	Proper Inspection Tests and Tools
Cement Sheath	5 years	EEH	Zonal Leakage: vertically to surface or to another zone, or horizontally to the adjacent casing	Distributed temperature sensing log (DTS). Ultra-noise image logs. Cement bond variable density log (CBL-VDL). Gamma ray log. Formation Integrity Test (FIT)
Casing String	5 years	EEH	Zonal leakage due to wearing, Collapse, etc.	Corrosion logs. Ultrasonic logs. Downhole camera. Electromagnetic casing logs, Caliper survey. Mechanical pressure integrity test.
Production Tubing	1 year	LH	Functionality loose and leakage due to wearing, scale, or erosion.	Corrosion logs. Ultra-sonic logs. Downhole camera. Caliper survey. Mechanical pressure integrity test.
Wellhead	3 years	EEH	Functionality loose and Leakage due to erosion or/and corrosion	A typical wellhead survey includes: Inspection of the wellhead, Annular pressure, Updated wellhead and tree schematic, Digital photos, Seal pressure tests, Radiography if required for problematic Valves, etc.
Subsurface Safety Valve (SSV)	2 years	MH	Functionality loose due to wearing due to corrosion, erosion or scale.	Leak tested in accordance with API 14B criteria. Pressure monitoring of an enclosed volume downstream of the valve (For situations where the leak-rate cannot be monitored or measured).
Packers	2 years	MH	Leakage and/or loose of functionality.	Mechanical pressure integrity test. Leak tested to the maximum expected differential pressure in the direction of flow. Alternatively, it shall be inflow tested or leak tested in the opposite direction to the maximum expected differential pressure, providing that ability to seal both directions can be documented. Sealing performance shall be monitored through continuous recording of the annulus pressure measured at wellhead level.

Table 5 A Holistic Well Integrity Inspection Schedule (part-2).

Well Barrier Type	Inspection Frequency	Failure Effect Severity	Potential Problems	Proper Inspection Tests and Tools
Fluid Barriers	1 year	LH	Pressure drop, leakage, …	Flow check (upon indications of increased return rate, increased volume in surface pits, increased gas content, flow on connections or at specified regular intervals). Measurement of fluid density during circulation. Measurement of critical fluid properties and compared with specified properties.
Conductor Pipe	5 years	HH	Surface leakage due to wearing, Collapse, etc.	Mechanical pressure integrity test.
Gas Lift Valves	1 year	LH	Functionality loose due to wearing due to corrosion, erosion or scale.	Leak tested in accordance with API 14B criteria.
Annulus Safety Valve (ASV)	2 years	MH	Functionality loose due to wearing due to corrosion, erosion or scale.	Leak tested in accordance with API 14B criteria.Function tested regularly as per a pre-defined frequency.
Packoff	2 years	MH	Functionality loose due to wearing due to corrosion, erosion or scale.	Mechanical pressure integrity test. Leak tested to the maximum expected differential pressure in the direction of flow. Alternatively, it shall be inflow tested or leak tested in the opposite direction to the maximum expected differential pressure, providing that ability to seal both directions can be documented. Sealing performance shall be monitored through continuous recording of the annulus pressure measured at wellhead level.
CIL	1 year	LH	Functionality loose due to wearing due to corrosion, erosion or scale.	Leak testing.
TRSV	1 year	LH	Functionality loose or/and leakage due to wearing due to corrosion, erosion or scale.	Leak tested in accordance with API 14B criteria.
Formation	5 years	HH	Shearing of casing, caving and perforation and permeability damage, etc.	Leak-Off Test (LOT). Formation Integrity Test (FIT).

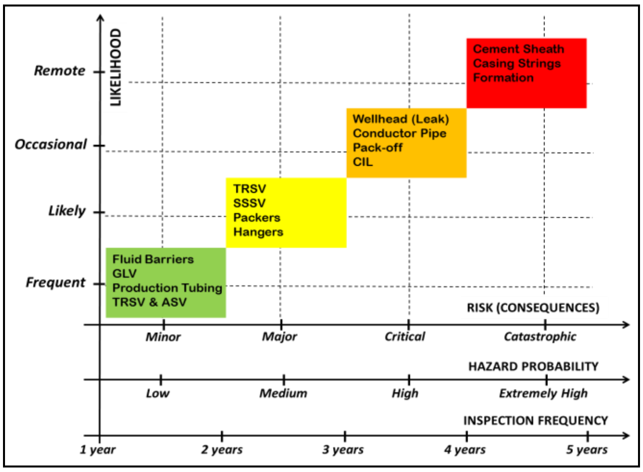

Figure 7 Risk based Inspection and Maintenance Matrix

LIMITATION OF THE STUDY

The well integrity inspection schedule and therisk based inspection and maintenance matrix are generalized guides for use when specific data is not available. However, for more accurate results, the history data of the area under consideration can be used to generate a study similar to this one.

CONCLUSIONS AND RECOMMENDATIONS

Oil and gas supply the world with energy by approximately 60% of all available energy sources.

Well integrity failures hit a company hard at every level. Hydrocarbon production is affected individuals may be hurt and environmental disaster is a potential risk.

Failures of wells of a specific time era are artifacts of that era; not reflective of wells completed today.

Review integrity test results and inspect production facilities more frequently during production facility closures.

Environment, in particular underground sources of drinking water (aquifers), must be protected during all oil and natural gas exploration, development, and production operations are conducted.

An inspection program should be set for oil and gas production assetsas shown in Figure 7 focuses on the following six primary well integrity surveys: 1) Wellhead valves integrity inspection and greasing. 2) Surface and Subsurface Safety Valves (SSV & SSSV) and Emergency Shut-Down (ESD) System functionality and integrity testing. 3) Annuli survey. 4) Landing base inspection. 5) Temperature survey. 6) Corrosion logging.

More data is needed to improve the developed well integrity inspection schedule.

A more specific inspection schedule is required based on environmental specifications differences, i.e. for HP/HT, Geothermal and highly corrosive fluids situations.

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