TransCanada Storage Well and Reservoir Life Cycle Integrity Management

November 2016
TransCanada’s Operational Management System

Facilities Integrity-Reliability Management Program

Storage Well and Reservoir Integrity Strategies/Plans

Engineering Standards – Design(8), Drilling/Servicing(14), Well Integrity(8), Reservoir Integrity (8)

Operating Procedures and Task Packages (~20)
Storage Integrity Management Strategies

Life cycle integrity management =

Engineering standards + Integrity plans, procedures, tasks

Safety is by design:

- Standards for design, construction, operation and abandonment, including engineering analysis procedures
- Active Control of well drilling / service work; disciplined, adaptive application of MOC across all well life cycle stages
- Integrity plans, with tasks including:
  - Data gathering and field-based monitoring
  - Mechanical integrity inspections of primary barriers
  - Engineering and geological analyses
  - Risk-informed decision making and resourcing
  - Performance tracking
Integrity plans link to 20 Operating Procedures for storage well work and data collection and to 38 well/reservoir engineering standards

**Hierarchy**

- Integrity Management Strategy
- Integrity Plans
- Operating Procedures and Task Packages
- Issue Log and Prioritization Model
- Risk Registers

One plan for all reservoirs and one plan for all wells...operating procedures and task packages may be specific to fields

Integrity Plans deconstruct “well” and “reservoir” into major parts...
### WELL
1) Pressure, Flow, and Fluid Monitoring
2) Casing Integrity Assessment
3) Storage Wellhead and Valve Maintenance
4) Well-site Documentation and Security Assessment
5) Well Completion/Performance Assessment
6) Well Work Planning/Execution
7) Emergency Response Planning/Training

### RESERVOIR
1) Gas Inventory Analysis and Monitoring
2) Reservoir boundary monitoring and protection
3) Reservoir performance assessment and monitoring

Tasks are listed by master task level and subtask, with timing/frequency requirement, responsibility (who), reason/driver for doing (regulatory, good practices, etc.), comments.

<table>
<thead>
<tr>
<th>MASTER TASK LEVEL</th>
<th>SUB-TASK</th>
<th>FREQUENCY</th>
<th>RESPONSIBILITY</th>
<th>DRIVER</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 Well and Reservoir Integrity Monitoring</td>
<td>1.1 annulus pressure checks; annulus gas samples</td>
<td>Monthly</td>
<td>res engr/field op techs</td>
<td>Best Practice API 1171, others</td>
<td>Where not automated. Manual reads of monthly annulus pressure are required to discover, track, report and correct anomalies - NOTE; RESERVOIR ENGR REPORTS IMMEDIATELY TO OPERATIONS MANAGER AND RESERVOIR SERVICES MANAGEMENT ANY ANOMALOUS BEHAVIOR ON ANNULAR SPACES. Develop investigative or corrective programs; estimate or calculate gas loss.</td>
</tr>
</tbody>
</table>
Time to Develop and Implement

- 2.5-3 years to develop integrity plans, procedures, engineering standards. Added knowledgeable, experienced part-time help over the duration in order to complete.

- Plus 1-2+ years to fully implement to solid foundation

- ~4-5 years to develop and implement

- Expect 1-2 years of cyclic continual improvement to feel we have foundation + maturity, 2nd version of documented integrity plans, procedures, and engineering standards

- Total time 5-7 years given extra help, motivated leadership, and total team commitment
Performance Tracking

- Task Tracking – data collection, planned/preventive maintenance completion and corrective action requirements and completions

- Issues lists
  - Well: well casing, annulus pressure, valve, ESD, well site, completion interval/deliverability
  - Reservoir: gas inventory pressure/volume, boundary security, deliverability and performance reliability

- Issue prioritization based on safety, issue potential severity ranking

**How do we know we have continual improvement mechanisms? What do we get out of this?**
ANR Storage Group - Well and Reservoir Integrity and Reliability Drivers, 2016 Work Program
TransCanada - US Storage Reliability / Integrity Issues Listing

Well Integrity Open Issues (All)

Well Integrity Open Criticals
State-Cold Springs A-2 (CS12-2)

Well Integrity Open Safety Issues (All)

Well Integrity Open Safety Criticals
NONE
Well Integrity Risk Assessment

Barrier Analysis

- Wellhead, seals, valves, pressure ratings
- Tubulars, pressure ratings, adjusted pressure ratings for condition assessments
- Other – packers, downhole equipment, pressure ratings
- Cement integrity, extent, quality
- Operating Limits
  - Maximum allowable annulus surface pressure (ISO 16530 method)
  - Maximum operating pressure and flow velocity, safety margin factors
- Operating Procedures, Inspection and Maintenance Plans
- Data documentation, well information form - ..\..\2016 Well Integrity Assessments\well profile and wellhead forms\CS1-5HD - 11 09 16.xlsx
Risk Analysis

Likelihood of primary containment failure

- past incidents, generic failure frequency
- condition assessment time-dependent trends, rates
  (corrosion and other deterioration mechanisms)
- time-independent potentials (impacts, etc.)

Consequence of primary containment failure

- secondary barriers: passive/technical containment,
  isolation, detection, control, human/organizational
- well flow capability (AOF tbg-limited at MOP)
- reservoir volume available (~15 day limit)
- population density - worker and public safety
- other: environmental, financial impact, service impact,
  regulatory, public perception
What is Values-Based, Risk-Informed Integrity Management?

Tolerable Risk Framework
- Intolerable Region - Risk Not Accepted, Reduce As Soon As Practical
- Tolerable Region - Manage to "As Low As Reasonably Practicable" (ALARP)
- Broadly Acceptable Region - generally no further risk reduction required

Diagram from UK HSE "Reducing Risks, Protecting People"

zone of ignorance
emphasize consequences avoidance
address societal concerns
address potential for irreversible /serious harm

increasing uncertainty of the likelihood

reliance on experience

consider generally known scenarios and consequences
conventional risk assessments

increasing uncertainty of the consequences
Risk Evaluation and Treatment

Tolerable Risk Framework

- Thresholds for safety; safety assessed for public, workers, nearby equipment/structures
- Environmental drivers – water, air, land/soil, non-human life and vegetation
- Service reliability, customer and public reputation
- Other financial impacts
- Assessment criteria – values thresholds and/or cost-benefit

Risk Treatment Decisions

- Options library
- Effectiveness assessment
- Data tracking
## Consequence-Driven Risk Treatment Decisions

<table>
<thead>
<tr>
<th>Financial Equivalence of Consequences</th>
<th>$10,000,000,000</th>
<th>$1,000,000,000</th>
<th>$100,000,000</th>
<th>$10,000,000</th>
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<th>$1,000</th>
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<th>$10</th>
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<td>Green/Yellow</td>
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<td>Green/Yellow</td>
<td>Green/Yellow</td>
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</tbody>
</table>

NOTE: well/casing failure is generally in “very unlikely” ranges, suggesting that risk treatment should be driven by probability-severity of consequences.

<table>
<thead>
<tr>
<th>Consequence</th>
<th>Likelihood</th>
<th>Surface SV failure per demand</th>
<th>Well failure, two barriers (tbg and csg) in excellent condition, per well-yr</th>
<th>Well failure, single barrier (casing, or casing and cement), per well-yr</th>
<th>Workover/re-entry incident rate, per event</th>
<th>Tbg failure, per well-yr (low end)</th>
<th>MTTR - SSSV systems</th>
<th>MTTR - tbg/pkr systems</th>
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</thead>
<tbody>
<tr>
<td>$10,000,000,000</td>
<td>.0000001 to .00001</td>
<td>.00001 to .001</td>
<td>.001 to .01</td>
<td>.01 to .1</td>
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<td>$1,000,000,000</td>
<td>.0000001 to .0001</td>
<td>.00001 to .01</td>
<td>.01 to .1</td>
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<tr>
<td>$100,000,000</td>
<td>.0001 to .001</td>
<td>.01 to .1</td>
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<tr>
<td>$10,000,000</td>
<td>.001 to .01</td>
<td>.1 to 1</td>
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<td>$100,000</td>
<td>.1 to 1</td>
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<tr>
<td>$10,000</td>
<td>.1 to 1</td>
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</table>
Consequence Drivers and Mitigations

Drivers

- Well flow potential and flow product composition
- Reservoir volume available to a well
- Proximity of well to population
- Population Density
- Worker/temporary human exposures
- Proximity to adjacent equipment/infrastructure
- Underground gas migration potential and pathways
- Environmental Factors, proximity and sensitivity
- Service Reliability factors – well importance to field performance

Mitigations (partial list)

- Isolation/Containment: secondary physical barriers, surface and subsurface
- Technical Control: flow shut off devices, fire suppression systems
- Human/Organizational Detection and Control: emergency response preparedness; data acquisition systems, alarms, and awareness of AOC; well intervention and control

RESEARCH:

1) HUMAN/ORG FACTORS IN PROCESS SAFETY

2) DATA ACQUISITION, MONITORING, ALARM – PROTOCOLS, STANDARDIZATION, RELIABILITY

3) TECHNICAL CONTROL BARRIER RELIABILITY
Quantitative example: Tubing/packer + casing vs. casing

analysis of LOC risk over 100 years...

Generic casing failure rate assumed 0.000023 per well/yr
Re-entry LOC rate 0.000215 per well entry
Two barriers 2-6x lower failure rate than generic casing failure rate
Tbg/pkr system MTTR is 15 to 30 years (3.3 to 6.7 re-entries in 100 yrs)
Casing MTTR assume 1-2 per 100 years

<table>
<thead>
<tr>
<th>re-entries over 100 years</th>
<th>re-entry LOC</th>
<th>wells</th>
<th>re-entry LOC</th>
<th>add Giff</th>
<th>total</th>
<th>add 0 to 1 well w/tbg for service</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>min</td>
<td>max</td>
<td>min</td>
<td>max</td>
<td>min</td>
<td>max</td>
</tr>
<tr>
<td>casing</td>
<td>1</td>
<td>2</td>
<td>0.000215</td>
<td>1</td>
<td>0.000215</td>
<td>0.00043</td>
</tr>
<tr>
<td>tbg</td>
<td>3.3</td>
<td>6.7</td>
<td>0.000215</td>
<td>1</td>
<td>0.00071</td>
<td>0.001441</td>
</tr>
</tbody>
</table>

LOC risk ratio, tbg/pkr vs. single well casing

3.00 6.37

3 to 6 times more LOC risk w/tbg

Note – even if casing failure likelihood increases to .0001, well re-entry risk drives total LOC risk due to increased re-entry due to inherently shorter tbg/pkr system MTTF/MTTR

CONTINUES TO SUGGEST THE IMPORTANCE OF HUMAN FACTORS IN PROCESS SAFETY (re-entry/workover LOC more of a driver than inherent casing/tubing failure)
## Recommendation Options

### Applicable TEPS: Gas Storage Facility Storage Well Integrity Plan (EDMS 008452312)

As prescribed from the Well Integrity Flow Charts, pick all options that apply. All potential remediation options require an immediate update to the FIRM Storage Well Integrity Issue Log and/or an IV study.

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Continue to operate without restriction per well integrity plans</td>
</tr>
<tr>
<td>2</td>
<td>Immediate action - set-downhole bridge plug, take well out of storage service</td>
</tr>
<tr>
<td>3</td>
<td>Immediate action - de-rate/limit maximum operating pressure</td>
</tr>
<tr>
<td>4</td>
<td>Enhanced data gathering (wellhead pressure, temperature, flow rate, etc) - MONTHLY</td>
</tr>
<tr>
<td>5</td>
<td>Enhanced data gathering (wellhead pressure, temperature, flow rate, etc) - WEEKLY</td>
</tr>
<tr>
<td>6</td>
<td>Enhanced data gathering (wellhead pressure, temperature, flow rate, etc) - DAILY</td>
</tr>
<tr>
<td>7</td>
<td>Enhanced casing annulus testing - MONTHLY</td>
</tr>
<tr>
<td>8</td>
<td>Enhanced casing annulus testing - WEEKLY</td>
</tr>
<tr>
<td>9</td>
<td>Enhanced casing annulus testing - DAILY</td>
</tr>
<tr>
<td>10</td>
<td>Enhanced casing inspection logging - NO MORE THAN 5 YEARS</td>
</tr>
<tr>
<td>11</td>
<td>Enhanced casing inspection logging - NO MORE THAN 10 YEARS</td>
</tr>
<tr>
<td>12</td>
<td>Enhanced casing inspection logging - NO MORE THAN 15 YEARS</td>
</tr>
<tr>
<td>13</td>
<td>Enhanced casing inspection logging - NO MORE THAN 20 YEARS</td>
</tr>
<tr>
<td>14</td>
<td>Additional logging - run cement bond, GRN, noise, caliper, casing inspection, and/or temperature log</td>
</tr>
<tr>
<td>15</td>
<td>Downhole remediation option - plug and abandon well</td>
</tr>
<tr>
<td>16</td>
<td>Downhole remediation option - install/repair tubing and packer</td>
</tr>
<tr>
<td>17</td>
<td>Downhole remediation option - install cemented liner</td>
</tr>
<tr>
<td>18</td>
<td>Wellhead remediation option - change-out/repair/paint wellhead valves/flanges/seals/bolts</td>
</tr>
<tr>
<td>19</td>
<td>Wellhead remediation option - pack-off wellhead seals</td>
</tr>
<tr>
<td>20</td>
<td>Wellhead remediation option - replace wellhead seals</td>
</tr>
<tr>
<td>21</td>
<td>Enhanced wellsite security - minimize encroachments (clear brush, remove trees, re-locate equipment, etc)</td>
</tr>
<tr>
<td>22</td>
<td>Enhanced wellsite security - install/repair physical barrier (heat shields, burms, fences, etc)</td>
</tr>
<tr>
<td>23</td>
<td>Enhanced wellsite security - install sub-surface safety valve</td>
</tr>
<tr>
<td>24</td>
<td>Downhole remediation option - install de-rate/pressure limiting downhole packer (limiting MOP)</td>
</tr>
<tr>
<td>25</td>
<td>Downhole remediation option - pressure test wellbore (MIT test)</td>
</tr>
<tr>
<td>26</td>
<td>Downhole remediation option - remedial cementing (grouting, perforate and squeeze, etc)</td>
</tr>
<tr>
<td>27</td>
<td>Wellhead remediation option - install/repair annulus pressure vents</td>
</tr>
<tr>
<td>28</td>
<td>Downhole remediation option - back-off and replace top joints of casing</td>
</tr>
<tr>
<td>29</td>
<td>Downhole remediation option - top-off annulus with corrosion inhibitor</td>
</tr>
<tr>
<td>30</td>
<td>Regional study - investigate regional geology and adjacent wells, additional logging</td>
</tr>
</tbody>
</table>

(bond, GRN, noise, caliper, casing inspection, temp) on adjacent wells, possible remediation of adjacent/plugged wells, addition of vent/observation wells
Additional Safety and Integrity Management

- Active Control of well drilling / service work
- Adherence to Contractor Safety Management Program and contracting qualifications and policies
- MOC adapted for all well and reservoir life cycle stages
- Conformance to Industry Standards
  - CSA Z341.1 (Canada)
  - API 1171
  - ISO 16530 (Well Integrity)
  - IADC/CAODC Drilling Practices
  - Enform safety practices
## Management of Change Process for the Storage Well Life Cycle

<table>
<thead>
<tr>
<th>Well Design</th>
<th>Well Drilling and Completion</th>
<th>Well Operation</th>
<th>Well Intervention</th>
<th>Well Abandonment</th>
</tr>
</thead>
<tbody>
<tr>
<td>change is initiated after the Well Design Basis Memorandum is completed</td>
<td>Planning: See Well Design stage</td>
<td>changes to operating status / limits, process, control, methods, measures, timing, or responsibilities</td>
<td>Planning stage</td>
<td>Planning stage</td>
</tr>
<tr>
<td>consult the CPMS Manage Project Design (EDMS 006740639)</td>
<td>Execution phase: Storage Reliability Well Drilling, Completion, and Intervention MOC Practice</td>
<td>Document Change Procedure (EDMS No. 007728670)</td>
<td>Storage Well Work Planning Procedure for Operation and Maintenance Work (EDMS No. 008902959) and Checklist (EDMS No. 008902948)</td>
<td>Storage Well Drilling and Servicing Practices (EDMS No. 008372584)</td>
</tr>
<tr>
<td></td>
<td>pre-completion phase: Wellsite Review and Turnover Procedure (EDMS No. 008873051) and Form (EDMS No. 008873036)</td>
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<td></td>
<td>Wellsite Review and Turnover Procedure (EDMS No. 008873051) and Form (EDMS No. 008873036)</td>
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<td>execution phase: Storage Reliability Well Drilling, Completion, and Intervention MOC Practice</td>
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<td>pre-completion phase: Wellsite Review and Turnover Procedure (EDMS No. 008873051) and Form (EDMS No. 008873036)</td>
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