Strategies for Cost-Effective, Reliable Long-Term Well Abandonment Barriers

Mike Cowan
Technology Director – CAZIT, Inc

Larry Wilson
Director – Knowledge Harvesting, Inc
Challenges

• Design and installation of effective long-term barriers is complex
  – Lack full understanding of how barriers and well systems work
  – Loss of competency within industry
  – Regulations/policies treat symptoms and restrict application of technologies to solve the problems

• The best currently available evaluation and diagnostic methods are inadequate and unreliable for:
  (1) barrier evaluation and verification
  (2) well abandonment planning
10 Things to Do That Improve Long-Term Reliability and Effectiveness of Barrier Systems (With Examples)

There are known technologies and proven strategies for creating effective long-term barriers – even with the uncertainties and challenges around diagnostics and verification.
10 Things To Do That Improve Barriers - 1

1. Design and install multi-component barriers
   – Cement alone, especially neat cement, is NOT a reliable barrier
   – Combine cement plugs with mechanical barriers and alternate materials

2. Install multiple barriers
   – Understand why and when multiple barriers should be used –
     even if they are not required by regulations

3. Remove all components in the interval where a barrier is installed
   – No ‘foreign’ materials/components imbedded in the barrier ‘matrix’
   – Seal, cut-off and remove control lines, tubulars, cables, etc

4. Include Alternative Materials for Barriers Inside Tubulars
   – Part of a multicomponent barrier system
   – Barite plugs
   – Combine barite plugs and resins/in-situ reaction materials to reduce cost and increase effectiveness
10 Things To Do That Improve Barriers -2

5. Use an Injectivity Test for every squeeze operation
   – Material and Placement Technique Selection

6. Use ‘In-Situ Reaction’ Materials for Annular Barriers
   – Perforate-and-Squeeze and/or Section-Milled intervals
   – Resins or Inorganic Reactive Materials Ahead of Cement
   – Consolidate materials in the annulus – penetrate formation to create internal barrier

5. Use cement formulations that meet functional concepts and property specifications for improved long-term bonding and interfacial sealing
   – Standardize minimum performance specifications for well abandonment sealants

8. Apply Industry State-of-the-Art Best Practices
   – Plug cementing
   – Quality control
   – Job Monitoring and recording
   – Post-job operations – waiting-on-cement time, etc
   – These are well known and documented (for over 50 yrs)
Material Selection for Remedial Treatments Based Upon Injection Test Data

### INJECTIVITY FACTOR, $\gamma = \frac{\text{Injection Pressure, psi}}{\text{Injection Rate, bbl/min}}$

*Higher Number = Smaller leak path*

#### INJECTIVITY FACTOR Ranges

- **< 2000**
  - API Cements
  - *Class C cement is typically the finest particle size of normal API cements*
- **2000-4000**
  - API Cement – Micro fine Cement Blend
  - 50-80% API Class C, G or H cement + 20-50% Micro fine Cement
- **4000-6000**
  - Micro fine Cements
  - Solids-free materials like resins/monomer
- **< 6000**
  - Solids-free monomer or resin sealant (low viscosity materials generally preferred)
  - Water-based Monomer Blend

#### Objective

- **Increasing sensitivity to material placement technique and methods for success**
- **Objective is to use material with highest potential for sealing leak path on first attempt**

#### Placement Technique

- **SPOT MATERIAL OPTIONAL**
- **MUST SPOT MATERIAL BEFORE SQUEEZE**

*Placement Technique is CRITICAL for Success: Requires Expert-Level Squeeze ‘Cement’ Advice*
Cement formulations with improved hydraulic isolation have the following characteristics:

- Reduced bulk and chemical shrinkage of cement
  - During and after setting of the cement
  - (Optionally) Post-set or plastic state expansion additives

- Increased compressibility of slurry

- No free water

- Low matrix permeability (OVER SERVICE LIFE UNDER CONDITIONS AT LOCATION)

- Increased ductility and elasticity

- *Anti-gas migration formulations required for gas wells – recommended for all applications*
Job Monitoring and Data Recording

Example of Data Monitored and Recorded During Cementing Operations

*The ONLY way to verify execution process and fundamental data needed for evaluation.*
9. Mechanically and chemically clean all surfaces at the interface of the barrier and well tubulars
   – There is NO reliable seal at an interface between cement and organic compounds (or materials with an organic coating)
   – There is an optimum ‘anchor profile’ for bonding/interfacial sealing

10. Apply Critical Decision-Making Process based upon accurate Interconnected Models for Well Abandonment Activities
    – Identify and address critical variables determining effectiveness
    – Develop functional requirements and specifications
    – Use functional requirements to select materials/component
    – Use functional requirements and critical specifications to develop procedures for installation
Purpose of Interconnected Critical Decision Models

- The ‘outputs’ of interconnected models are:
  - Knowledge Retention / Legacy of Experts
  - Technology Transfer / Accelerated Training Programs
  - Actualize information/knowledge – for use/application
  - Simplified understanding of complex systems
  - Critical decision support modules for effective well abandonment barrier design and installation

- The ‘output’ of a Critical Decision Module is:
  - Framework of functional requirements for effective long-term barriers
    - Materials
    - Placement Techniques/Procedures
    - Alignment between materials-access-placement techniques
  - Specifications for critical properties
  - Requirements for engineering design/analysis work
  - Requirements for lab data/testing
  - Sensitivity testing/analysis
Interconnected Model Example
(Of This Presentation)
Summary

• What it takes to achieve effective long-term isolation and integrity is known.

• There is untapped potential for more reliable, effective barriers that are cost-effective to design and install
  
  – The industry has (barely) scratched the surface of what is possible!

• Five things that would make a positive difference:
  
  – Understand well systems (wells as a SYSTEM – including barrier systems)
  – Develop Critical Decision Models for well construction and abandonment
    • Making decisions on critical variables that ‘make/break success’ for long-term isolation
    • Competency and consistency
  – Develop minimum standard specifications for abandonment sealants
  – Develop engineering and laboratory support data for materials as alternatives/supplements to (Portland) cements
  – Focus on verification/quality assurance and control during abandonment barrier installation
API WG05: Well Abandonments

• **Work Group Charge:** “Identify literature and gaps associated with well plugging and abandonment for both offshore and onshore environments. Present findings to serve as foundation to develop a Recommended Practice (RP)”

• **Members**
  - Joe Shine – Chair
    - (Joe.ShineJr@gmail.com and/or Joseph.ShineJr@Aramco.com)
  - Jerry Calvert – Advisor

• **Forward Plans:**
  - Complete identified literature review
  - Evaluate categories
  - Document development
RESOURCE SLIDES

THESE SLIDES WILL NOT BE SHOWN DURING THE PRESENTATION.

MAY BE SHOWN DURING DISCUSSION, IF APPROPRIATE.

RUN IN ‘SLIDE SHOW’ MODE TO VIEW ANIMATIONS
Categories of Variables Affecting Long-Term Barrier Effectiveness and Well Integrity

Wells are mechanical systems imbedded in a complex, highly variable geosystem. What happens in one affects the other...with different orders of response time and magnitudes of effects.

- WELL CONDITION:
  - SCP, corrosion, scale, casing condition, operating parameters, etc.

- WELL DESIGN AND QUALITY OF CONSTRUCTION:
  - Casing program, annular barrier design, borehole stability and integrity, well path and tortuosity, drilling practices, completion type, etc.

- CEMENTING PROCESS
  - Cementing is 80-90% Placement + 10-20% Materials

- MATERIAL PROPERTIES:
  - Cement, Relationships between Pipe-Cement-Formation

- PRESSURE AND TEMPERATURE CHANGES/CYCLING
  - (Over the life of the well)

- GEOMECHANICS:
  - In-situ stresses, change in stresses along borehole, change in stresses in cement and pipe, field effects

- CHEMISTRY:
  - Corrosion and chemical resistance of casing and annular barrier materials

- GEOLOGY/GEOCHEMISTRY:
  - Formation type, structure, chemical composition, formation fluid chemistry, porosity, permeability, etc.

A SYSTEMS APPROACH IS ESSENTIAL

There is a complex relationship and interaction between variables within each of these categories that directly affects long-term integrity of both the well and geosystem.
**BARRIER BASICS**

- **How Most Well Barriers Work:**
  
  *In the absence of adhesive bonding, barriers rely on low matrix and interface permeability, length/surface area and an effective radial stress to maintain a seal at any interface in a well system.*

  Currently, the industry has no tools to directly measure (sealing) stress along a well.

- **Pressure Testing is the ONLY measure of barrier effectiveness**
  - NEGATIVE and POSITIVE TESTS – *IN THAT ORDER*
  - The smaller the leak – the longer the duration of the test required to identify it
  - IF IT CANNOT BE PRESSURE TESTED...ITS EFFECTIVENESS IS UNDETERMINED
  - Testing after installation does not insure long-term effectiveness

- **There is only one chance to ‘get it right’ for each barrier**
  - IT IS NEARLY IMPOSSIBLE TO REMEDIATE A LEAKING BARRIER
Multiple, Multi-Component Barriers Example

Concepts and Example Configuration 1

**EXAMPLE MATERIALS**

**Cement Plug**
Portland or other inorganic cement with long-term structural/matrix durability

**Chemical Resistant Resin**
(Furan, MF, Epoxy, etc. or Polymer Concrete)

**Mechanical Isolation Tool**
(Packer, Bridge Plug, Retainer, etc.)

**COMPONENTS AND FUNCTION**

1 - Long-Term Durability Component
- (Often) Required by regulations

2 - Secondary/Resilient Seal Component
- Resin based sealant. Place and apply pressure to squeeze. Penetrates and seals matrix of mechanical isolation tool.
- Can be solids-filled with no filtration control (high fluid loss) to reduce cost and increase durability
- Chemical adhesion to casing/surfaces (even oil wet). Resilient. Material properties maintain seal under changing stresses.
- Secondary seal

3 - Initial Isolation Component
- Initial primary seal
- Serves as base for location and placement of other components
- Location, integrity and sealing can be verified prior to installation of other components
Multi-Component Annular Barriers: Perf-and-Squeeze Case with Without Circulation Up Annulus

Concept and Example Configuration 3

EXAMPLE MATERIALS

Cement Plug
Portland or other inorganic cement with long-term structural/matrix durability

Mechanical Isolation Tool
(Packer, Retainer, etc.)

Chemical Resistant Resin
(Furan, MF, Epoxy, etc. or Polymer Concrete)

Mechanical Isolation Tool
(Packer, Bridge Plug, Retainer, etc.)

Squeeze Below Retainer

COMPONENTS AND FUNCTION

1 - Long-Term Durability Component
- (Often) Required by regulations

2 - Isolation/Material Placement Component

3 - Secondary/Resilient Seal Component
- Resin based sealant. Place and apply pressure to squeeze. Penetrates and seals matrix of annular materials/ formations
- Chemical adhesion to casing/surfaces (even oil wet). Resilient. Material properties maintain seal under changing stresses.
- Secondary seal

4 - Initial Isolation Component
- Initial primary seal
- Serves as base for location and placement of other components
- Location, integrity and sealing can be verified prior to installation of other components
Multi-Component Annular Barriers: Perf-and-Squeeze Case with Without Circulation Up Annulus

Concept and Example Configuration 2

Spot Resin Material Prior to Squeezing
Optionally, use retainer depending upon injectivity

EXAMPLE MATERIALS

Cement Plug
Portland or other inorganic cement with long-term structural/matrix durability

Chemical Resistant Resin
(Furan, MF, Epoxy, etc. or Polymer Concrete)

Mechanical Isolation Tool
(Packer, Bridge Plug, Retainer, etc.)

COMPONENTS AND FUNCTION

1 - Long-Term Durability Component
- (Often) Required by regulations

2 - Secondary/Resilient Seal Component
- Resin based sealant. Place and apply pressure to squeeze. Penetrates and seals matrix of annular materials/ formations
- Chemical adhesion to casing/surfaces (even oil wet). Resilient. Material properties maintain seal under changing stresses.
- Secondary seal

3 - Initial Isolation Component
- Initial primary seal
- Serves as base for location and placement of other components
- Location, integrity and sealing can be verified prior to installation of other components
Multiple, Multi-Component Annular Barriers: Perf-and-Squeeze Case with With/Without Circulation Up Annulus

Concept and Example Configuration

EXAMPLE MATERIALS

Cement Plug
Portland or other inorganic cement with long-term structural/matrix durability

Mechanical Isolation Tool
(Packer, Retainer, etc.)

Chemical Resistant Resin
(Furan, MF, Epoxy, etc. or Polymer Concrete)

Mechanical Isolation Tool
(Packer, Bridge Plug, Retainer, etc.)

COMPONENTS AND FUNCTION

1 - Long-Term Durability Component
- (Often) Required by regulations

2 - Isolation/Material Placement Component

3 - Secondary/Resilient Seal Component
- 3A = Neat Resin  
  - Resin based sealant. Place and apply pressure to squeeze. Penetrates and seals matrix of annular materials/ formations
  - Chemical adhesion to casing/surfaces (even oil wet). Resilient. Material properties maintain seal under changing stresses.
  - Secondary seal

4 - Initial Isolation Component
- Initial primary seal
- Serves as base for location and placement of other components
- Location, integrity and sealing can be verified prior to installation of other components
Situations Where Multiple Barriers Are Needed

Concepts and Example Configuration 5

Example where MULTIPLE BARRIERS are (also) required

EXAMPLE MATERIALS

Cement Plug
Portland or other inorganic cement with long-term structural/matrix durability

Barite Plug / Drilling Fluid
- Modified or unmodified carrier fluid
- Modifications include in-situ reaction chemistries (Resins, etc)

Cement Plug
Portland or other inorganic cement with long-term structural/matrix durability

Mechanical Isolation Tool
(Packer, Retainer, etc.)

COMPONENTS AND FUNCTION

1 - Long-Term Durability Component
(Often) Required by regulations

2 - Secondary/Resilient Seal Component
- Resilient. Material properties maintain seal under changing stresses.
- Secondary seal.

3 - Long-Term Durability Component
- Control lines should be sealed prior to cutting
- This seal cannot be considered reliable since there are components imbedded into the matrix of the barrier.
- Another set of barriers above this is required for long-term reliability

4 - Production Packer, Tubing, Control Lines
- Serves as base for location and placement of other components
- Location, integrity and sealing can be verified prior to installation of other components
Benefits of Monomer/Resin/In-Situ Reaction Technologies

Penetrates material in annuli
- Consolidates material into cohesive mass
- Good adhesion to rock/steel surfaces
- Low (no) permeability
- Resilient material – good material properties
- Material properties better for long-term sealing of perforations.

Penetrates small openings/leak paths

Variety of techniques can be used for effective placement
- Some materials are self-consolidating – can be dropped through fluid in well and form a solid sealant

Many set quickly – ‘right angle set’
- Beneficial to stop/control flows (gas)
- Reduce WOC/Waiting Time

Much higher material cost than cements, but cost effective in complex, high cost well operations

Poor/limited industry support/expertise for their application
P&A Cement Formulation Example

• Total Shrinkage < 2% (as low as possible)
• API Fluid Loss: < 50 mL/30 minute (at 300 F, 1000 psi)
• Free water: Zero
• Permeability*:
• Elastic Modulus*: Poisson Ratio*:
• Silica content: 35-50% by weight of cement
• 0.05 to 0.1 gal/sk surfactant compatible with all additives and cement
  – Addition of surfactants requires operational planning and may require additional metering and injection equipment
  – Latex emulsions contain surfactants and may provide beneficial effects of these concentrations
• Optional additives
  – Post-set expansion agents – shallow plugs (< 200 F BHST approx.)
  – Gas-generating agent – severe gas migration control
WG05: Well Abandonments

CSOEM – SC 10 – Subcommittee on Well Cements

2015 Exploration & Production Winter Standards Meeting

Joe Shine – Chair
28 January 2015
Outline

• Charge
• Introduction
• Update
• Forward Plans
• Discussion
WG Charge

• “Identify literature and gaps associated with well plugging and abandonment for both offshore and onshore environments. Present findings to serve as foundation to develop a RP”
Introduction

• Members
  ➢ Joe Shine - Chair
  ➢ Jerry Calvert – Advisor

• Contact information
  ➢ Joe.ShineJr@gmail.com
  ➢ Joseph.ShineJr@Aramco.com
Update

• Documents identified for literature review
  - API Bulletin E3, Reaffirmed, 2000
  - API STD 65-2, Dec. 2010
  - API RP 96, March 2013
  - TX TAC Title 16 Part 1 Chapter 3, Rev. March 2014
  - UK Oil & Gas Guidelines, Issue 4, July 2012
  - NORSOK D-010, Rev 4, June 2013
Update

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>TPA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Position</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HCs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AQ</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OH</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>API E3</th>
<th>UK</th>
<th>SB</th>
<th>TRRC</th>
<th>API STD 65-2</th>
<th>API RP 96</th>
<th>NOR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Requirement</th>
<th>SPECIAL CONSIDERATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPA</td>
<td>ST</td>
</tr>
<tr>
<td>PA</td>
<td></td>
</tr>
<tr>
<td>CC</td>
<td></td>
</tr>
<tr>
<td>HCs</td>
<td></td>
</tr>
<tr>
<td>AQ</td>
<td></td>
</tr>
<tr>
<td>OH</td>
<td></td>
</tr>
<tr>
<td>CH</td>
<td></td>
</tr>
</tbody>
</table>

TPA = temporary abandonment  
PA = permanent abandonment  
CC = circumferential coverage  
HCs = hydrocarbon bearing zones  
AQ = aquifers  
OH = open hole including completions  
CH = cased hole including completions  
ST = side tracking  
RA = radioactive  
AF = annular fluids  
PFZs = potential flow zones  
CS = casing stubs  
OS = offshore  
DHE = downhole equipment
Forward Plans

• Complete identified literature review
  ➢ API RP 96
  ➢ NORSOK D-010, Rev 4, June 2013

• Evaluate categories
  ➢ White spaces
  ➢ Similarities, differences, potential cost implications

• Document development
  ➢ Review outlines of similar documents
  ➢ Minimum requirements for categories
  ➢ Alignment with applicable documents and/or workgroups