Study produces supercement for annular seal and long-term integrity in deep, hot wells

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EXPLORATION FOR NATURAL gas shifts more and more to deeper reservoirs. Encouraging finds and increased demand reinforce the push for drilling wells with target formations deeper and deeper underground in hotter, higher-pressure conditions. This trend presents many obstacles in drilling, completion and production from these deep wells in high-pressure, high-temperature (HPHT) environments.

Durability of annular seals created using Portland cement ranks high on this list of obstacles. Harsh conditions, huge investment cost of well construction, and high cost of seal remediation in these harsh, remote environments increase the necessity for annular seal durability.

Industry authorities estimate that remediation of failed cement seals in deep, hot wells costs the industry more than $100 million each year. Environmental damage potential and lost production while wells are shut in for remediation increase the real cost of cement seal failure. While additives and well-designed placement techniques can increase the chances of achieving long-term zonal isolation in HPHT wells, the industry continues to report high incidence of annulus gas pressure on deep, hot wells. This pressure occurrence is most likely caused by annular seal failure resulting from mechanical failure of Portland cement.

In early 2004, the National Energy Technology Laboratory awarded CSI Technologies LLC funding for a 3-year study to develop new cementing systems that would endure the harsh HPHT environment. This article summarizes results of that study.

APPROACH

The development approach that was followed included:

- Evaluation of downhole conditions that induce high stresses on annular seals in HPHT wells.

Figure 1: To investigate cement compositions’ mechanical properties after curing at HPHT conditions and direct seal durability, this HPHT annular seal test was devised.

- Analysis of cement system properties that affect seal integrity and criteria for a good sealant.
- Laboratory evaluation of cement properties by conventional and newly developed measurement techniques.
- Modification of cement compositions and properties to improve important physical and mechanical properties over those of current Portland cements.
- Selection of top one or two candidates for HPHT field application development.
- HPHT field application.

WELL ATTRIBUTES, CEMENT PROPERTIES

Review of past research and finite element modeling identified well environmental and operational conditions that induced stress gradients across annular seals in HPHT wells. The significant contributors were:

- High temperature and high pressure.
- Deviation.
- Narrow annulus.
- CO₂ and H₂S.
- Multiple pressure stimulation treatments.
- Extreme thermal gradients when starting or stopping production.

For over a century, the work horse of sealants for these applications has been Portland cement. However, Portland cement is not the ideal sealant for many of the applications encountered in a well. It is too brittle, and tensile strength is too low to be...
durable under cyclic stress conditions encountered downhole. Therefore, cement seal reliability is reduced with well operations over times reliability reduction is accelerated with HPHT conditions.

The ideal cement for creating durable annular seals in HPHT wells must possess excellent tensile strength. Additionally, the ideal cement material would be resilient and survive repeated stress cycles. Finally, the ideal cement would be resistant to chemical attack.

LABORATORY EVALUATION

More than 200 sealant formulations were screened in the initial laboratory investigation. All these formulations possessed potential for improved mechanical properties that would produce more durable annular seals than the Portland cement currently in use. Compositions ranged from modified Portland cements to non-Portland inorganic cements to settable organic compounds. From this initial screening, five cement compositions, two non-Portland and three modified Portland, were identified for further investigation.

The further investigation included measurement of mechanical properties after curing at HPHT conditions and direct seal durability measurement via a specifically developed laboratory test termed “HPHT Annular Seal Test.”

In this test procedure, a cement sheath was constrained by a steel pipe inside the annulus and an outer formation simulated by a metal or polymer sleeve (Figure 1). Variation of the outer sleeve material simulates variation of formation mechanical properties.

After a cement composition is cured in the test fixture at high temperature, a pressure differential is placed across the deal and the inner pipe is pressurized repeatedly to simulate cyclic stresses imposed by completion, production and intervention operations. Cumulative work done to the system as a result of the pressure cycles was tracked along with the occurrence of seal failure as evidenced by pressure communication across the seal. These data were analyzed to determine and compare quantitative seal durability.

IMPROVED SEALANTS

Two sealant formulations emerged from the extensive HPHT lab testing as potential improvements over Portland cement sealants currently used. These compositions were pre-stressed cement and a new epoxy resin named UltraSeal R Sealant. Pre-stressed cement is Portland cement with a large concentration of high-temperature expansion additive. The expansion additive alters the crystalline structure of the cement after set under confined conditions, thereby inducing trapped compressive pre-stresses in the crystalline matrix of the seal. This is analogous to pre-stressing concrete structural members with tension placed on reinforcing bar and greatly increases the seal’s apparent tensile strength. This pre-stress provides significantly higher resistance to tensile stresses developed in a cement sheath, which must be relieved before the material goes into tension increasing the effective tensile strength of the material.

Shear bond strength of the pre-stressed cement is significantly greater than that of normal cement when the system is sufficiently confined (Figure 2). Sufficient confinement is critical to this system’s performance since the amount of expanding agent added will cause the solid material to expand until it self-destructs in an unconfined state.

UltraSeal R Sealant offers a totally different seal performance compared with Portland-cement-based sealants. Mechanical properties, including tensile strength and shear bond strength, are much more suited to withstanding hoop stresses imposed on an annular seal. Additionally, this new material is ideally suited to HPHT conditions. It can be formulated for placement at up to 300ºF and is chemically inert. Three major advances in the chemistry of UltraSeal R over previously used epoxy sealants include:

• It does not shrink after set.
• It is not sensitive to water contamination
• A column of UltraSeal R Sealant will set with gas percolating through it and form a gas tight seal.

Selected test results for these two sealants are presented in Table 1, along with those measured for a standard Portland cement composition with silica. These results illustrate the improved resiliency of the two new sealants over currently used Portland cement. Annular seal testing indicates a greater than 10-fold increase in seal function for UltraSeal R Sealant and a 5-fold increase for pre-stressed cement over that of Portland cement. Large increases in shear bonds of the two new sealants also contribute to the improved performance.

ECONOMIC IMPACT

One of the primary objectives of the Deep Trek program was to lower the costs of drilling and operation of deep, hot gas wells.

Table 1 shows test results of pre-stressed cement and an epoxy resin called UltraSeal R Sealant along with measurements for a standard Portland cement composition with silica. Results show improved resiliency of the two new sealants.

<table>
<thead>
<tr>
<th>System</th>
<th>Density (lb/gal)</th>
<th>Compressive Strengths (psi)</th>
<th>Compressive Young’s Modulus (psi)</th>
<th>Tensile Strengths (psi)</th>
<th>Shear Bond (psi)</th>
<th>Annular Seal (in-lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class H + 35%bwoc</td>
<td>16.6</td>
<td>4790</td>
<td>4.08 x 10^6</td>
<td>705</td>
<td>260</td>
<td>1.9 x 10^6</td>
</tr>
<tr>
<td>Silica Flour</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prestresse d Cement</td>
<td>19.0</td>
<td>3190</td>
<td>2.50 x 10^6</td>
<td>280</td>
<td>3540</td>
<td>9.7 x 10^5</td>
</tr>
<tr>
<td>UltraSeal R Sealant</td>
<td>16.5</td>
<td>5550</td>
<td>3.56 x 10^6</td>
<td>3690</td>
<td>1830</td>
<td>1.7 x 10^6 + *</td>
</tr>
</tbody>
</table>

*Pressure cycling was stopped before the seal failed.
Economic impact evaluations indicate that pre-stressed cement can meet this objective easily in primary cement applications. The cost of this composition is comparable with current Portland cements. Expected decrease in remedial work dictated by seal failure would result in decrease in cost of completing and producing an HPHT well.

This composition has the advantage of being based on Portland cement. Therefore, application of this modified composition would not represent a significant cost to the pumping service company.

Ultraseal R Sealant is much more expensive than currently used cement compositions. This expense, which can range up to 20 times more than Portland cement, results from the fact that Ultraseal R sealant is a synthetic organic material that costs significantly more to make than Portland cement. However, this cost can be justified in remedial applications in which the new sealant is much more successful at shutting off gas than Portland cement. Ultraseal R Sealant is economical to apply in remedial applications when both cost and performance are considered.

FIELD APPLICATIONS

UltraSeal R Sealant has been used on over 50 field applications at temperatures ranging from 55°F to 295°F. All the applications thus far have been remedial and under conditions in which ordinary Portland cements have failed in the past. Even with these difficult conditions, the applications have yielded an overall success rate of over 90%. The volumes for these applications have ranged from 5 gallons to 20 barrels. In general, significantly smaller amounts of UltraSeal R Sealant are required to fix a problem than with Portland cement.

Additionally, chances of successfully correcting a problem the first time with Ultraseal R sealant are 5 to 10 times higher than with Portland cement. This field trial has proven the material is mixable and placeable with standard oilfield mixing and pumping equipment. Additionally, the function of the sealant in oilfield fluids has been confirmed.

Pre-stressed cement has not been applied in a field application thus far. However, applicable blend compositions have been designed in the laboratory for temperatures ranging from 200°F to 350°F. Additionally, a full-scale mixing test using field mixing equipment confirmed that the composition can be blended, mixed and pumped.

SUMMARY

The results of this study produced improved sealants for HPHT wells. Pre-stressed cement is applicable for primary cementing applications while UltraSeal R Sealant is useful as a remedial sealant. Application of these sealants in HPHT conditions should result in significantly improved annular seals. In turn, the resulting well operation should be easier and more effective with fewer interventions to repair gas leakage.

This article is based on results from a project supported by NETL under the Deep Trek program. The goal of Deep Trek is the development of new technologies that promise to dramatically reduce deep drilling costs and bolster drilling efficiencies. Complete results from this cooperative program will be available under reference number DE-FY26-03NT41896 on NETL’s website in the fourth quarter 2007.