MODIFICATION OF WHITE'S SQUEEZE INJECTION SCALE FOR USE WITH CLASS C CEMENT AND ULTRA-LOW FRACTURE GRADIENTS

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ABSTRACT

Over a number of years, the reference tool developed by Grant, White, Smith & Miller' and commonly referred to as "White's Injection Scale" has been widely accepted as a useful mechanism for planning and execution of cement squeeze processes in shallow and low pressure formations worldwide. In early 2001, refinements to the injection scale were developed that focused on applying many of the same concepts to two Permian Basin peculiarities: 1) The nearly exclusive usage of API Class C cement in squeeze operations shallower than 10,000 feet, and, 2) the high incidence of fracture gradients so excessively low that a full column of nearly any liquid is not supportable by the formation being squeezed.

The modified injection scale is presented and explained. Incremental improvements provided by the modified scale are examined, and application case histories are described.

INTRODUCTION

Over the last four decades, an immense knowledge base has been built surrounding squeeze cementing techniques and processes[2-9]. Most of this information was put together by large operators, major oil companies, and pumping service companies that had the resources and labor to closely examine the statistics associated with thousands of squeeze operations worldwide. As these companies experimented with a wide variety of downhole situations, a broad consensus was reached by a number of authors as to "best practices".

Gulf Oil, Chevron, and various combinations and subsidiaries of these companies were especially active in this specialized industry. Grant, White, Smith & Miller' were able to summarize much of what the industry had learned to date, and as a part of their effort, developed a tool called the "Injection Scale". The scale was simply a diagram (see Figure 1) that recognized different approaches to squeeze cementing, depending on whether injection into the formation was either "loose" or "tight". Later, the diagram evolved into a chart (see Figure 2) that was not only effective during the design stage, but was intended to be useful in real-time operations on-location. The process has been proven repeatedly worldwide, and has gained relatively wide acceptance in the field.

It was recognized that, while the concepts behind the existing Injection Scale and chart were sound, there were basically three situations that it did not address:

1. The Injection Scale was designed to be utilized in situations where true "squeezing" of a cement slurry was taking place. The formation to be squeezed had to be permeable enough to accept fluids at rates high enough to be practical (+0.25 – 0.5 bpm) and yet remain under the fracture gradient. If such conditions do not exist, then the "squeeze" process essentially becomes a remedial cementing technique that places whole cement in the formation much as in a fracture-stimulation treatment.
2. "Loose" and "tight" injection can have multiple root causes. The Injection Scale and chart addressed most, but not all of these causes. In the Permian Basin, each of the causes for "loose" or "tight" injection is naturally present in some areas. In a few of these, "loose" injection can be extreme and can have multiple causes present at the same time.
3. Though the work done by Grant, White, Smith & Miller included two case histories with class C cement, the existing chart is oriented more toward class **H,** G, and **A** cements. The Permian Basin typically utilizes Class C (generally more thixotropic than **H,** G, or **A)** for almost all squeeze work shallower than 10,000 ft. In addition, extensive use of highly thixotropic slurries (those containing high percentages of gypsum) is present in the Basin.

These limitations led to the development of a "Modified White's Injection Scale" that attempted to address the above and more clearly define alternatives that were available for both design work and real-time on-location decision making in the Permian Basin.

DEFINITIONS

In order to fully understand design and action steps, it was desired to clearly define the terms that will be constantly referred to.

- ***Squeeze cementing*** **———** The placement of cement across a permeable rock area, causing dehydration of the slurry due to a pressure differential and subsequent diversion of that slurry to another portion of permeable rock area.

- ***Remedial cementing*** ——— The placement of whole cement slurry in a desired position. Some dehydration may occur, but the primary intent is to place slurry without significant dehydration or diversion.

- ***Loose injection*** ——— Pumping (or fluid leaking off) at high rates and low pressures at the same time. This situation can generally have 2 causes or combination of causes: a) If the zone has very high permeability, then fluid may flow with very little resistance and remain under the horizontal in-situ stress. b) Occasionally, the in-situ minimum stress has been altered by the production of reservoir fluids to a point at which the fracture gradient in the near-wellbore area is less than 0.50 psi/ft. In this case, if the permeability of the zone is low, hydraulic fracturing may take place any time we increase the hydrostatic head by any substantial amount, whether we want it to or not, and regardless of the injection rate we try to maintain.

- ***Tight injection*** ——— Pumping (or fluid leaking off) at low rates and high pressures at the same time. There are also two causes for this. a) If the zone has low effective permeability, then Darcy flow through the porous media will require high pressure differentials, regardless of whether fracturing pressures are exceeded or not. b) Abnormally pressured reservoirs will normally have a high in-situ stress, and therefore a high fracture gradient and a high pump-in pressure. In this case, one must be clear to include only those porous media with low permeability in the category "tight". An abnormally pressured zone with high fracture gradient and high permeability will exhibit a very rapid leakoff after pumping has ceased, and therefore such should be categorized as "loose".

SPECIAL CASE OF ULTRA-LOW FRACTURE GRADIENTS

The Permian Basin of West Texas and Southeastern New Mexico has a number of "loose" Field/Formation combinations that exhibit fracture gradients of 0.4 – 0.5 psi/ft. Most of these situations fall into one of three categories:

a) Formations with ultra-low fracture gradient and low permeability (e.g., portions of the Upper Spraberry).
b) Formations with ultra-low fracture gradient, low reservoir pressure (drained), and a propped fracture that effectively exposes the pump-in fluid to a large surface area of matrix (e.g., Upper and Lower Spraberry, Dela ware). In this case, during pre-squeeze injection, their may be enough surface area exposed that it is impossible to quickly and easily determine whether a low, moderate, or high permeability situation is dominant.
c) Low pressure dolomitic reservoirs in Southeastern New Mexico with moderately low fracture gradients (0.45 – 0.55 psi/ft) and vugular or cavernous porosity.

In all three of these situations, the term "screaming vacuum" is often a standard scenario anytime any slurry or combination of slurries of any density is pumped past the wellhead. For the most part, operators have gravitated to two-system squeezes: the first system is usually a highly thixotropic mixture of Class C and gypsum, and the second, a moderate or low fluid loss slurry. Relatively large quantities of both lead and tail slurries are pumped, and a large volume between the tool and the squeeze target is designed. The displacement volume is approximated as closely as possible by allowing the vacuum to pull displacement water directly from pumping service company displacement tanks. In most cases, it is desirable to place the lead [thixotropic] slurry completely outside existing tubulars prior to the first hesitation. When possible, the low-fluid loss system remains at or near the tool for hesitations.

Occasionally, even the above measures are not sufficient to stop cement from displacing itself beyond the leak or perforations. A number of exotic techniques have been utilized[10], most with limited success. A sodium silicate solution pumped ahead of cement (with appropriate spacers) can be effective if adequate calcium ion is available in the formation water for immediate reaction.

SPECIAL CASE OF ULTRA-LOW PERMEABILITY

If a reservoir's permeability is so low that reasonable pump rates (>0.25 to 0.5 bpm) are not possible without fracturing the rock, then an operator must abandon hope of squeezing, and simply place cement in and beyond that portion of the wellbore that he believes will solve the problem. This process is then defined as "remedial cementing", and is usually

accomplished with the use of a retainer.
Sometimes this situation is mistakenly diagnosed when low injection rates and high pressures are encountered, when in fact it may be due to excessive skin — blockage at the perforations with mud filtrate, weighting agents, unknown solids, etc. There are, in all practicality, only three ways to determine whether perforations are blocked or not: either perform and analyze a pump-in test much in the same way a minifrac is executed, spot and pump a small amount of acid into the zone[5], or re-perforate. Operators have generally chosen to acidize or re-perforate as the most cost-effective solution.

Once it has been determined (or predicted) that a zone truly exhibits ultra-low permeability (regardless of the fracture gradient), then a remedial treatment should be designed that does not include significant hesitations ("pump it—place it—sting out—reverse out").

APPLICATION OF THE MODIFIED INJECTION SCALE AND CHART

The new scale and chart was introduced in a short course at the 2001 Permian Basin Oil and Gas Recovery Conference in Midland, Texas. Several operators elected to utilize the process in both the design phase and in executing on-location decisions. Figures **3** and 4 show pressure/rate charts from typical squeezes. It was not possible to track all applications of the Modified Injection Scale and Chart, so an overall success or failure rate is not reported.

FUNCTION OF THE SCALE AND CHART

The Injection Scale has as its objective the determination of the downhole conditions that will materially impact both design decisions and real-time hesitation decisions. The Scale utilizes "tight" and "loose" injection as the barometer for decision classification, then makes specific recommendations in the Chart based on that classification.

Once a formation has been classified as "tight", "loose", or somewhere in between, the Chart addresses action steps as follows:

Design phase: volume of cement to be pumped.
Design phase: decision on whether to specify a single slurry or two slurries.
Design phase: fluid loss and thickening time specifications for slurries.
Design phase: volume, in bbl, required for effective hesitating.
On-location phase: recommendations for hesitating (y/n).
On-location phase: recommendations for duration of the first hesitation.

MODIFICATIONS TO WHITE'S INJECTION SCALE AND CHART

Figure 3 presents the modified chart. Specific alterations:

- Although Class C slurries generally exhibit thickening times comparable (or slightly longer) than Class H, G, or A, they develop gel strength sooner, and are more thixotropic". The impact of this property on squeezing is obvious: leaving Class C slurries at zero shear rates for the same length of time as Classes H, G, and A could be disastrous. Although it has been shown that excessive retardation and thickening time of various oilfield cements do not have much impact on compressive strength development[12], the modified chart takes into account the slightly thixotropic nature of Class C, and appropriately shortens the recommended hesitations times. It has been recognized that the success of the original Injection Scale was in part due to "fewer and longer" hesitations, so the Modified White's Injection Scale continues the tradition of lengthy hesitations, pushing the envelope for the majority of systems specified in the Permian Basin. The Modified Injection Scale and Chart applies only to Class C cement.
- The new scale and chart recognizes the reality of fracturing ultra-low fracture-gradient zones, and incorporates highly thixotropic slurries" [those containing substantial percentages of additional gypsum] into the lead systems when appropriate. It also suggests action when utilizing these slurries.
- The new scale and chart clearly recognizes "loose" and "tight" injection, separating the various root causes of each as defined above, and suggesting appropriate action.

CONCLUSIONS

The Modified White's Injection Scale and Chart for Class C Cement presents incremental improvements that assist in Permian Basin squeeze design and execution. The Scale and Chart take into account the almost exclusive use of Class C cements shallower than 10,000 ft, and they assist in the extreme cases of fracture gradients so low that a column of any fluid cannot be supported.

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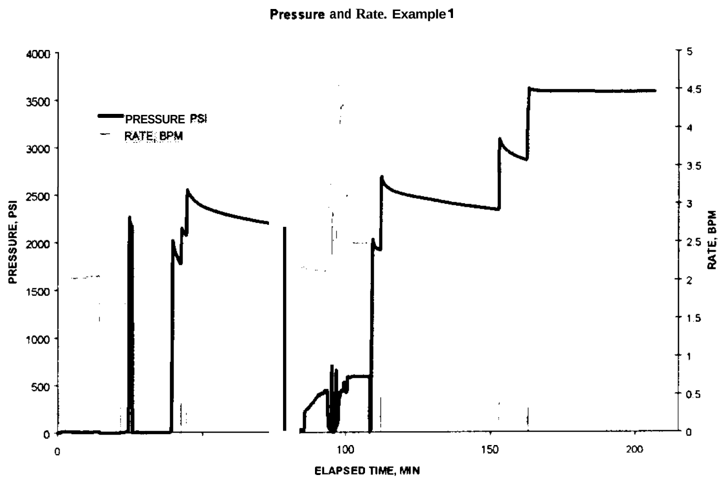

Figure **1** - Example Single-System Squeeze, “Moderate” Injection

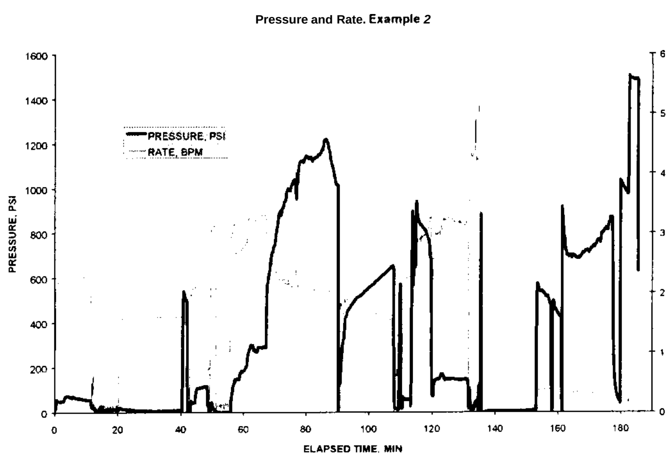

Figure 2 - Example Two-System Squeeze, “Loose” Injection

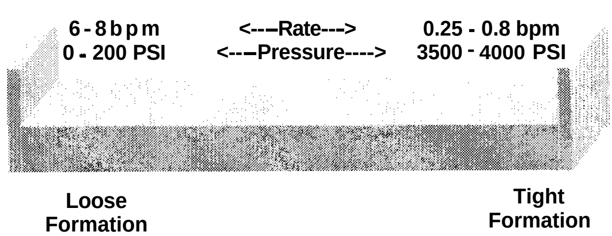

Figure 3 - Origianl Injection Scale. From Grant, W.H., Jr., White, R.L., Smith, R.C., and Miller, A.G.: “Successful Squeezing of Shallow and Low Pressure Formations”. This scale was the basis for later work that evolved into the “Injection Chart”.

THE INJECTION SCALE
Chart Form

← VACUUM		NO RATE →
LOOSE INJECTION	**MODERATE INJECTION**	**TIGHT INJECTION**
Low Pressure Low or High Rate	Moderate Pressure Low or Moderate Rate	High Pressure Low Rate Only
Large Volume Cement	Moderate Volume Cement	Small Volume Cement
*Two Slurry Design	One or Two-Slurry Design	One-Slurry Design
**Lead Slurry: 200 - 400 ml fluid loss 2 hr pump time	**Lead Slurry: 150 - 250 ml fluid loss 2 hr pump time	Do not run lead slurry
**Tail Slurry: 100 ml fluid loss or less 3 - 4 hr pump time	**Tail Slurry: 100 ml fluid loss or less 3 - 4 hr pump time	**Tail slurry only 50 ml fluid loss or less 3 - 4 hr pump time
**6 - 10 bbl slurry for hesitating	**4 - 8 bbl slurry for hesitating	**2 - 4 bbl slurry for hesitating
Hesitation, maybe running	Hesitation or running squeeze	Running, maybe hesitation squeeze
Long first hesitation 40 - 45 minutes	Long first hesitation 30 minutes	Short first hesitation 15 - 20 minutes

*Loose injections at or near the extreme may require a lead slurry change to a more viscous or thixotropic type slurry and or a reactant pre-flush ahead of and in addition to the lead slurry.

**Values for fluid loss and hesitation cement volume are to show relative order. While they are fairly accurate they may require adjustment for a particular squeeze situation.

Figure 4 - The Original Injection Scale And Chart, Presented in Various Training Sessions for Chevron, but Most Recently Presented at the 2001 Southwestern Petroleum Short Course in Lubbock, Tx.

MODIFIED WHITE'S INJECTION SCALE AND CHART FOR CLASS C CEMENT

VACUUM (Loose) ⟷ NO RATE

LOOSE INJECTION	MODERATE INJECTION	TIGHT INJECTION
Low Pressure Low or High Rate	Moderate Pressure Low or Moderate Rate	High Pressure Low Rate Only
Large Volume Cement	Moderate Volume Cement	Small Volume Cement
Two Slurry Design	One or Two-Slurry Design	One-Slurry Design
Lead Slurry' 200 - 400 ml fluid loss 2 hr pump time[3]	Lead Slurry' 150 - 250 ml fluid loss 2 hr pump time[3]	Do not run lead slurry
Tail Slurry 100 ml fluid loss or less 2 - 3 hr pump time[3]	Tail Slurry 100 ml fluid loss or less 2-1/2 - 3 hr pump time[3]	Tail slurry only 50 ml fluid loss or less 2-1/2 - 3-112 hr PT[3]
6 - 10 bbl slurry for hesitating[3]	4 - **8** bbl slurry for hesitating[3]	2 - 4 bbl slurry for hesitating[3]
Hesitation, maybe running	Hesitation or running squeeze	Running, maybe hesitation squeeze
Long first hesitation 30 - 40 minutes[2]	Long first hesitation 25 - 30 minutes[2]	Short first hesitation 15 - 20 minutes

Figure 5 - The Modified White's Injection Scale and Chart for Class C Cement