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PLT-Calibrated Permeability: A Breakthrough in Carbonate Characterization

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Introduction

- Modeling fluid flow in carbonates a challenge.
  - Especially “excess perm” zones (vugs & fractures)
- Improved using **Apparent Permeability** derived from Production (PLT) Logs – “APERM”
- Distributes well-test permeability-thickness (KH) to reservoir layers
- Inherent match to fluid flow improves accuracy
- Better management of multi-layer reservoirs improves recovery
Outline

• Where technique can be used
• How it works
• Assumptions and Potential Uncertainties
• Use of Pulsed Neutron Acid Effect to distinguish high skin vs. low perm
• Examples
• Independent validation of Process Improvement with Pulse Testing
• Lessons learned, Best Practices, and Challenges
Where Can APERM Technique Be Used?

• Any multi-layer reservoir, but most needed in Carbonates

• Best to acquire baseline flow profile on new completion before onset of multi-phase flow.
  – Known viscosity if single phase flow
  – Multiphase flow will complicate, but technique may still result in more realistic permeability

• Wells in mature reservoirs on artificial lift could be logged by injection profile
Calculation Procedure

- Normalize to KH from welltest
- Use as reference to adjust transform perm.
  - Why? Preserve Wireline scale resolution in perm
Excess Permeability (Eperm)
-Falls above matrix perm range.

- Due to fractures, vugs
  - Matrix perm transform will under-predict
- The most important to correctly characterize
- Technique quantifies Excess Perm zones
Impact of Potential Uncertainties

- Errors less than factor of 2 deemed not critical
- Fluid Properties Uncertainty insignificant
- Pressures: Within 10% if SIP used- Minor impact
- Drainage/wellbore radius: Minor impact
- Flow Rate: Within 10%, minor impact
- Skin: The most significant assumption

A factor of two variation in perm is within the noise.
Pressures

• Flowing pressure measured during PLT.
  – Not fatal if unable to achieve stability

• Layer Pressure: Simple if reservoir on single gradient.

• Differential Depletion:
  – Different pressures for different layers
  – Measure layer pressure using multi-rate PLT and Selective Inflow Performance (SIP) analysis
Differential Depletion

- Some zones deplete more rapidly due to higher perm or more extensive production
Differential Depletion

- Some zones deplete more rapidly due to higher perm or more extensive production
- Pressure differences = significant crossflow during shut-in
- If not accounted for, can have large errors in calculated perm.
SIP Technique

- Used to measure shut-in layer pressure.
- No layer need ever be static.
- Extrapolate to static layer pressure using Inflow Performance Relationship (IPR).
- Above bubble point, the IPR is a straight line.
  - Two points adequate to define line
- If flow below bubble point, IPR is curved, need 3-4 rates.
Rate/pressure pairs from multi-rate PLT are plotted for each zone. That pressure for which rate = 0 is the layer pressure.
Layer Pressure Uncertainty

- Long shut-in time prior to PLT reduces uncertainty because initial SI passes are at stable pressure.
- Inability to achieve stable flowing pressure in tight wells has less impact.
Skin Factor

- Skin factor assumption is most important
- Normal range = 10X difference in flow rate, thence calculated perm
- If flow >> predicted, perm must be >> predicted
  - Cannot be the result of over-stimulation
Skin Assumptions

• First pass: Use Skin (S’) from pressure transient
  – OK if all zones are well stimulated

• High Uncertainty When:
  – Well not stimulated
  – Large amounts of lost circulation material (LCM) used during drilling
  – Non-diverted stimulation
  – EPERM zone takes all acid, leaving remaining pay unstimulated
Acid Effect on Pulsed Neutron (PNC) Logs

- Acid distribution is key uncertainty on many wells
- Assess by running PNC logs to measure acid effect.
- Chlorine from spent acid imbibes into connate water, increasing sigma ($\Sigma$).
  - If no free water production ($Sw$ is irreducible), effect is permanent
- Compare post-stim $\Sigma$ with synthetic pre-stim $\Sigma$
  - Difference (acid effect) shaded in magenta in subsequent graphics
- If acid effect observed, and no potential damage mechanisms since stim, we assume $S'= -4$ (or pressure transient $S'$)
Example of Reduced Permeability

- Flow from bottom half of zone much lower than predicted.
  - Damage? Low Perm?
- Acid effect key info.
- PNC porosity lower than old open hole neutron
- Conclusion: Perm originally too high due to bad neutron log
  - Perm reduced with confidence
Example of Excess Perm

5-10X “Perm Boost” needed to explain high production rate from upper zone

Excess Perm shaded
Pressure Transient Tests Used

Single Well Pressure Buildup

Pressure
Rate

Pressure Permeability Skin Boundaries

Inter-well Pulse Tests

Active Well  Observation Well

Pressure (hundreds of PSI)
Rate

Inter-well connected pore volume (phi-h)
Inter-well connected permeability (kh)

Pressure (< 1 PSI)
Derivative Pressure
Validation of Model Improvement Using Pulse Tests

- Several inter-well pulse tests done to assess connectivity
- Poor pressure match with old transform perm based model
- New APERM model match much better
Pulse Test Validation

- **Simulated - Old Model**
- **Simulated – New Model (APERM)**
- **Actual Pressure Response**
- **Derivative – New Model**
- **Derivative – Actual Pressure**
- **Derivative – Old Model**

Graphs showing pressure and derivative over time, with pulsing well rate and date markers.
Incorporating APERM into Geologic Model

Tengiz Case Study

- PLT on 80% of wells
- Wells with good quality APERM used to populate geologic model
- Significant changes to permeability field were made
Restoration of Heterogeneity

- Perm transforms reduce heterogeneity
- Models based on transform perm tend to underpredict heterogeneity.
  - Breakthrough occurs earlier than predicted
- APERM restores heterogeneity to model
Lessons Learned & Remaining Challenges

- **Lessons Learned:**
  - Need stimulation to ensure profile reflects reservoir
  - PLT profiles critical to manage multilayer reservoirs

- **Remaining Challenges:**
  - Assumptions on skin for damage vs. low perm
  - High perm zones can dominate, obscuring lesser zones
  - Seeking optimum method of inter-well property distribution
Conclusions

• Method is robust workflow for incorporating PLT and Pressure Transient data into earth model
• Method is an improvement over static log based transform permeability
• Overcomes difficulties in predicting perm from well logs, particularly in Carbonates
• Effective at identifying and characterizing excess perm layers.
• Restores natural perm heterogeneity
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