Reservoir Engineering Aspects of Unconventional Reservoirs

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Brief Biography — Tom Blasingame

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Brief Biography: Blasingame

● Role:
  — Professor, Texas A&M U.
  — Holder of the Robert L. Whiting Professorship
  — B.S., M.S., and Ph.D. degrees from Texas A&M U. (PETE)

● Counts: (October 2012):
  — 10 Ph.D. Graduates
  — Over 100 Technical Articles

● Recognition:
  — Distinguished Member of the Society of Petroleum Engineers (2000)
  — SPE Distinguished Service Award (2005)
  — SPE Distinguished Lecturer (2005-2006)
  — SPE Uren Award (2006)
  — SPE Lucas Medal (2012)

● Current Research Activities:
  — Nano-Scale Flow Phenomena
  — Evaluation of Well Performance Data for Shale/Liquids-Rich Systems
  — Numerical Modeling of Ultra-Low Permeability Reservoir Systems
Reservoir Engineering Aspects of Unconventional Reservoirs

Orientation

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Orientation: EUR for UR Systems

● Facts of life...
  ■ Analogs (... need to understand uncertainty (very high))
  ■ EUR (... minimum of 12-18 months for high confidence)
  ■ IP (... may be uncorrelated with EUR)
  ■ Early Productivity (... poor wells don't get better)
  ■ Time-Rate Analysis (... not representative? (chaotic operations))

● Comments on recovery...
  ■ Early EUR? (... can this be meaningful?)
  ■ EUR = f(t)? (... how do we incorporate this?)
  ■ Well Spacing? (... is this really the holy grail?)

● Mechanisms to estimate recovery...
  ■ Time-Rate Analyses (... may not be sufficient)
  ■ Time-Rate-Pressure Analyses (... requires a reservoir model)
Orientation: Reservoir Engineering of UR Systems

● Things that SHOULD help…
  ■ Production Logs  (... but just a snapshot in time)
  ■ Optimal Proppant Design/Placement  (... obvious, but)
  ■ Stimulation Stages/Perforation Clusters  (... geology + logs)

● Things that DEFINITELY WOULD help…
  ■ Measured $\rho_{wf}$  (... yes, this is my favorite song)
  ■ Downhole Fluid Sampling  (... sooner or later)

● QUANTIFYING reservoir properties?
  ■ Pressure Transient Analysis  (ultra-low $k$?)
  ■ Production Analysis  ($p_{tf}$ may not be sufficient)
  ■ Petrophysical analysis  (theory ≠ application)

● Liquids-Rich Systems?
  ■ Fluid-Flow Mechanisms  (what is really flowing where?)
  ■ PVT  (near-critical fluids are not trivial)
  ■ Improved Recovery  (we all know this is coming…)
  ■ Fit-for-Purpose Stimulation  (higher $F_{cd}$, more complexity)
  ■ Artificial Lift  (fact of life…)
Orientation: "Everybody Has An Opinion"

Never-Ending Arguments…

- SRV (... what is it, really?)
- Desorption (... significance? timing? relevance?)
- Stimulation Fluids (... where does it go? does it matter?)
- Microseismic (... crystal ball, roulette wheel, or roadmap?)
- Pressure-Dependent Whatever (... so what?)
- Natural Fractures (... if/when/why/what?)
- Dual Porosity/Dual Permeability (... what about the physics?)
- Well Placement (vertically) (... when does it matter?)
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How Small is Small? (nano-scale pores)

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Pore-Scale: Characteristic Behavior

a. Systematic "mapping" of the inter-relation of petro-physical properties. Note that Archie observed that permeability was "connected" to saturation, porosity, and electrical properties — but the relationship was vague, as it remains today.

b. Crossplot of formation (resistivity) factor versus permeability ($F = A/k^b$).

c. Severe influence of clay minerals in this reservoir system — production shown to be uniquely tied to reservoir quality and effectiveness of well stimulation.

Legend: SEM Micrographs
A. (240X) Grains with clay overgrowths.
C. (600X) Microporosity and clay filling.
D. (1400X) Rosettes of chlorite (note illite deposition).
**Pore-Scale: Characteristic Behavior**

\[ k = a(\phi - c)^b \]

Plot of Measured Permeability (md) Versus Porosity (fraction), Hazlett Well 103 (34 Samples)

\[ k = c \exp[\beta \phi] \]

\[ k = x a \phi^b + (1-x) \alpha \exp[\beta \phi] \]

Plot of Measured Permeability (md) Versus Porosity (fraction), Hazlett Well 103 (34 Samples)
Pore-Scale: Nelson Pore/Molecule Size Chart

Question(s):
● How small are pores in shale gas? *Note that the size of the pores is on the order of 5-10 times the size of the fluid molecule.*

Perspective:
● The concept of pores and pore throats begins to break down at these scales.
● The flow path can be as small as 10-20 molecular diameters (or less).

Issues:
● How do the fluids move?
  — Darcy flow?
  — Dispersion (gases)?
  — Knudsen flow?
● How are the fluids stored?
  — In the organic matter?
  — Adsorbed?
  — Another mechanism?

Each green line is x10 SMALLER scale.

Figure 2. Sizes of molecules and pore throats in siliciclastic rocks on a logarithmic scale covering seven orders of magnitude. Measurement methods are shown at the top of the graph, and scales used for solid particles are shown at the lower right. The symbols show pore-throat sizes for four sandstones, four tight sandstones, and five shales. Ranges of clay mineral spacings, diamondoids, and three oils, and molecular diameters of water, mercury, and three gases are also shown. The sources of data and measurement methods for each sample set are discussed in the text.
Pore-Scale: Shale Pore Space (Barnett Example)

Question(s):
● Where is/are the gas/liquid stored? There is porosity, often in the organic materials.
● Why is the phase behavior of many shales "near critical"? Nanopores?

J. Sedimentary Research, v. 79/12 (2009)
Morphology, Genesis, and Distribution of Nanometer-scale Pores in Siliceous Mudstones of the Mississippian Barnett Shale
Loucks, R.G., R.M. Reed, S.C. Ruppel, and D.M. Jarvie

Fig. 5.—Nanopores associated with organic matter in the Barnett Shale. A) Elliptical to completely rounded nanopores in an organic grain. Darker materials are organic. BSE image. Blakely et al., 2010.4 m. B) Angular nanopores in a grain of organic matter. SE image. Blakely et al., 2010.4 m. Accelerating voltage = 10 kV; working distance = 6 mm. C) Tubelike pore throats connecting elliptical pores (white arrows). Pore-throat diameter < 20 nm. Blakely et al., 2010.4 m. D) Additional tubelike pore throats connecting elliptical pore (white arrows). Pore-throat diameter < 20 nm. Blakely et al., 2010.4 m.

Fig. 6.—Secondary electron images showing variations in nanopore morphology in organic matter. A) Very small (15–46 nm diameter), nearly spherical nanopores. Total porosity in the field of view = 5.2%. Blakely et al., 2,106.4 m. Accelerating voltage = 4 kV; working distance = 5 mm. B) Larger nanopores (590 nm diameter) showing complex internal structure resembling pillars. Blakely et al., 2,106.4 m. Accelerating voltage = 10 kV; working distance = 6 mm. C) Tubelike pore throats connecting elliptical pores (white arrows). Pore-throat diameter < 20 nm. Blakely et al., 2,106.4 m. D) Additional tubelike pore throats connecting elliptical pore (white arrows). Pore-throat diameter < 20 nm. Blakely et al., 2,106.4 m.
**Pore-Scale: Petrophysics/Permeability**

**Gas Flow**

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b. Knudsen "microflow" model (Modified from Karniadakis and Beskok, 2002).

c. Microflow model and correlation, "fully implicit" formulation.

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**SPE 107954**

Improved Permeability-Prediction Relations for Low Permeability Sands


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Computation Equivalent Liquid Permeability versus Klinkenberg-Corrected Permeability — Lower Cotton Valley No. 2

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\[
\frac{k_e}{k_m} = \left[1 + \frac{128}{15\pi^2} \tan^{-1} \left( \frac{d_0}{p_m k_m \phi \phi_2} \right) \right]^{0.4} \left[1 + \frac{4}{1 + \frac{1}{d_0 \frac{1}{p_m} k_m \phi \phi_2}} \right]^{0.4}
\]
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Schematic Time-Rate Analysis

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Time-Rate: Schematic Production Performance Plot

- The schematic represents the most common approach to EUR.
- Used CAREFULLY, this should be valid.
"Plug and Perf" System: Each STAGE has a certain number of perforation "clusters" (typically 4)

"FracPoint" (and other such) Systems: Each STAGE is isolated and stimulated
Time-Rate: Flow Regimes — *Multi-Fracture Horizontal Well*

- **1:2 Slope (high $F_{cD}$)**
  \[ q_{LF}(t) = a_{LF} \left[1/\sqrt{t}\right] \]

- **1:4 Slope (low $F_{cD}$)**
  \[ q_{BLF}(t) = a_{BLF} \left[1/\sqrt{t}\right] \]

- **Formation Linear Flow Regime**
- **Compound Linear Flow Regime**
- **Elliptical Flow Regime**
- **Bilinear Flow Regime**
- **Transition Regime**

Early-Time Regimes are HYPERBOLIC?

\[ q(t) \equiv q_i/\left[(1 + bD_i t)^{1/b}\right] \]

Logarithm of Production Time

For Shales: | days | weeks | months | years | decades | ...

Discussion:
- 1:2 Slope $\rightarrow$ $b=2$ (*HIGH* fracture conductivity).
- 1:4 Slope $\rightarrow$ $b=4$ (*LOW* fracture conductivity).
- *This is a schematic, it overly simplifies the system.*
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Emerging Ideas/Tools for Time-Rate Analysis

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Numerical Model Considers:
- Reservoir Layering.
- $k_v/k_h$ ratio.
- Fracture Length, $x_f$.
- Fracture Conductivity, $F_{cD}$.

Analysis/Validation Approach:
- Fit $q(t)$ with Arps' hyperbolic relation.
- Compare reserves to model at 30 years.
**Vertical TG/SG Wells: Elliptical Flow Domination**

b. Elliptical flow type curve solution — low fracture conductivity case.

b. Elliptical flow type curve solution — high fracture conductivity case.


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SPE 106308 (2007)

Evaluation of the Elliptical Flow Period for Hydraulically-Fractured Wells in Tight Gas Sands — Theoretical Aspects and Practical Considerations

S. Amini, D. Ilk, and T. A. Blasingame, SPE, Texas A&M U.
Modern Decline Analysis: *Power-Law Exponential Rate*

**Question(s):**
- Can we use time-rate analysis as a diagnostic? *Yes, use* $D(t)$ *and* $b(t)$ *functions.*
- Differentiation of $q(t)$ data? *Intuition is against it — but it is possible with some careful editing and robust differentiation.*

**SPE 116731 (2008)**
*Exponential vs. Hyperbolic Decline in Tight Gas Sands — Understanding the Origin and Implications for Reserve Estimates Using Arps’ Decline Curves*

**PLE Rate Relation:**

\[ q(t) = \hat{q}_i \exp[-D_\infty t - \hat{D}_t t^n] \]

**Decline Function:** $D(t)$

\[ D(t) \equiv -\frac{1}{q(t)} \frac{dq}{dt} \]

\[ \approx D_\infty + n\hat{D}_t t^{-(1-n)} \]

**Hyperbolic Function:** $b(t)$

\[ b(t) \equiv \frac{d}{dt} \left[ \frac{1}{D(t)} \right] \]

\[ \approx \frac{n\hat{D}_t (1-n)}{[n\hat{D}_t + D_\infty t^{(1-n)}]^2} t^{-n} \]

**Points:**
- $b(t)$ and $D(t)$ are evaluated continuously.
- $D(t)$ trend indicates "power-law" behavior.
Modern Decline Analysis: \textit{Stretched Exponential Relation}

**Question(s):**
- When was the "stretched exponential" model first cited in the Petroleum literature? \textit{Jones (1942) and Arps (1945)}.
- Is there a physical representation of the SE model? \textit{Yes, a sum of exponentials}.

**Non-Petroleum Literature:**
- Kohlrausch (1854).
- Decays in random, disordered, chaotic, heterogeneous systems.

\textbf{SPE 119369 (2009)}

\textit{Assigning Value to Stimulation in the Barnett Shale: A Simultaneous Analysis of 7000 Plus Production Histories and Well Completion Records}

P. Valkó, Texas A&M U.

\textbf{Valkó (2009)}

\[ q(t) = \hat{q}_i \exp\left(-\hat{D}_i t^n\right) \]

\textbf{Jones (1942) and Arps (1945)}

\[ q(t) = q_o \exp\left[-\left(t / \tau\right)^n\right] \]

\[ q(t) = q_o \exp\left[\frac{-D_o t^{m-1}}{100 (m-1)}\right] \]
Modern Decline Analysis: Continuous EUR

Question(s):
- How to estimate EUR "continuously"?
  Use "segments" of the time-rate history to evaluate EUR regularly in time.

SPE 132352 (2009)
Continuous Estimation of Ultimate Recovery
S. Currie, D. Ilk, and T. Blasingame, Texas A&M U.

\[
q_g(t) = \frac{q_{gi}}{(1 + bD_i t)^{(1/b)}}
\]  
[hyperbolic]

\[
q_g(t) = \hat{q}_{gi} \exp[-D_{\infty} t - \hat{D}_t^n]
\]  
[PLE]

\[
q_g(t) = q_{gi} - D_i G_p \quad [G=q_{gi}/D_i] \quad [q_g(t) \text{ vs. } G_p(t)]
\]

c. CEUR governing equations.

a. Continuous EUR (CEUR) process plots.

b. CEUR hyperbolic, PLE, and \( q-G_p \) summary plots.

d. CEUR master summary plot (all results).
Modern Decline Analysis: Time-Rate Diagnostics

SPE 135616

Hybrid Rate-Decline Models for the Analysis of Production Performance in Unconventional Reservoirs

D. Ilk and S.M. Currie, Texas A&M U.; D. Symmons, Consultant, J.A. Rushing, Apache, and T.A. Blasingame, Texas A&M U.

\[ \beta_{q,cp}(t) = - \frac{d \ln(q)}{d \ln(t)} = - \frac{t}{q} \frac{dq}{dt} \]

a. $\beta$-derivative — Holly Branch Wells.

b. $\beta$-derivative — "Shale Gas Field C" Wells.

c. $\beta$-derivative — All Models (Holly Branch Well).
Modern Production Analysis: \textit{Integration of Results}

**SPE 140556 (2011)**

Integration of Production Analysis and Rate-time Analysis via Parametric Correlations — Theoretical Considerations and Practical Applications

D. Ilk, DeGolyer and MacNaughton, J.A. Rushing, Apache, and T.A. Blasingame, Texas A&M U.

**Power-Law Exponential Relations:**

\[ D(t) \equiv -\frac{1}{q} \frac{dq}{dt} \approx D_\infty + n\hat{D}_i t^{-(1-n)} \]

\[ q(t) = \hat{q}_i \exp[-D_\infty t - \hat{D}_i t^n] \]
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"Unconventional" Time-Rate Analysis

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**Time-Rate: Modified Hyperbolic Rate Relation**

*Modified Hyperbolic Rate Relation:*

\[
q(t) = \begin{cases} 
\frac{q_{i,\text{hyp}}}{(1 + bD_it)^{1/b}} & (t < t^*) \\
q_{i,\text{exp}} \exp[-D_{\text{lim}} t] & (t > t^*) 
\end{cases}
\]

- **Decline Function:** \( D(t) \)
  \[
  D(t) \equiv -\frac{1}{q} \frac{dq}{dt}
  \]

- **Hyperbolic Function:** \( b(t) \)
  \[
  b(t) \equiv \frac{d}{dt} \left[ \frac{1}{D(t)} \right] \equiv \text{constant}
  \]

- **\( \beta \) Function:** \( \beta(t) \)
  \[
  \beta(t) \equiv t \left| \frac{dq}{q \frac{dt}{dt}} \right| \equiv t \ D(t)
  \]

**Discussion:**
- \( qDb \) functions are **DIAGNOSTIC**.
- \( D(t) \), \( b(t) \), and \( \beta(t) \) are evaluated **continuously** (at all points).
- This shale gas case exhibits \( b=2 \) behavior \( \rightarrow q = a\sqrt{t} \) (Linear Flow).
- Appears to be "hyperbolic," but this is just the Linear Flow portion.
Time-Rate: Power-law Exponential Relation

- **Observed Behavior of Decline Parameter (D):** *(from data)*

\[
D(t) \equiv -\frac{1}{q} \frac{dq}{dt} \approx D_\infty + n \hat{D}_i t^{-(1-n)}
\]

- **Flowrate Solution:** *(derived from D(t) behavior)*

\[
q(t) = \hat{q}_i \exp[-D_\infty t - \hat{D}_i t^n]
\]

- **Literature:**
  - Kohlrausch (1854).
  - Kisslinger (1993)
  - Decays in random, disordered, chaotic, heterogeneous systems (e.g., relaxation, aftershock decay rates, etc.).

Valkó (2009)

\[
q(t) = \hat{q}_i \exp[-(t/\tau)^n]
\]

Jones (1942) and Arps (1945)

\[
q(t) = q_0 \exp \left[ -D_o t^{m-1} \right]
\]

\[
\frac{100 (m-1)}{
}
\]
**Time-Rate: Power-Law Exponential Rate Relation**

**PLE Rate Relation:**

\[ q(t) = \hat{q}_i \exp[-D_\infty t - \hat{D}_i t^n] \]

**Decline Function: \( D(t) \)**

\[ D(t) \equiv -\frac{1}{q(t)} \frac{dq}{dt} \]

\[ \approx D_\infty + n\hat{D}_i t^{-(1-n)} \]

**Hyperbolic Function: \( b(t) \)**

\[ b(t) \equiv \frac{d}{dt} \left[ \frac{1}{D(t)} \right] \]

\[ \approx \frac{n\hat{D}_i (1-n)}{[n\hat{D}_i + D_\infty t^{(1-n)}]^2} t^{-n} \]

**\( b \) Function:** \( b(t) \)

\[ \beta(t) \equiv t \frac{1}{q(t)} \frac{dq}{dt} \equiv t \frac{D(t)}{D_\infty} \]

**Discussion:**
- \( qDb \) functions are DIAGNOSTIC.
- Power-law exponential relation is derived from: \( D_\infty + n\hat{D}_i t^{-(1-n)} \)
- No direct analog to hyperbolic case.
- This is a "tight gas" reservoir case.
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Time-Rate-Pressure Analysis

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**Time-Rate-Pressure Analysis: East Texas Gas Well (Vertical)**

- **a.** Log-log analysis plot.
- **b.** Log-log "Blasingame" plot.
- **c.** Corresponding PTA plot for this well.
- **d.** Simulated model response compared to data.

Time-Rate-Pressure Analysis: **Flowback Analysis**

**SPE 135607**

A Comprehensive Workflow for Early Analysis and Interpretation of Flowback Data from Wells in Tight Gas/Shale Reservoir Systems


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**a. Crossplot — All wells: \( q_g \) versus \( q_w \).**

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**b. Crossplot — All wells: \( p_{cf} \) versus \( t \).**

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**c. Crossplot — All wells: \( \Delta p^2/q_g \) versus \( t \).**
Discussion: Marcellus PA Cases (normalized to similar derivative shape)
- Very strong grouping for all three wells — unique character.
- Grouping = \( f(\text{Permeability, Well Completion, Fracture Conductivity}) \).
Discussion: Montney PTA Cases (normalized to similar derivative shape)
- These trends are grouped according to derivative character.
- Grouping = $f$(Permeability, Well Conditions, Fracture Conductivity).
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Practical Aspects

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Practical Aspects: Stimulation

Discussion:
- Maximizing SRV (Stimulated Reservoir Volume)
  - Build Complexity → Slickwater
  - Build Conductivity → Hybrid/Gel Systems
- Future Stimulation Challenges:
  - Can we "rubblize" the reservoir?
  - Can we "pulverize" the reservoir?
  - Can we do this with little or no water?

"You only produce from what you frac ..."
Anonymous
Reservoir Engineering Aspects of Unconventional Reservoirs

Summary

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Summary: Reserves

● Shale Gas/Shale Liquids Resources
  ■ In-place resources are well understood.
  ■ Flow mechanisms are NOT well understood.
  ■ These systems MUST BE STIMULATED to yield economic rates.

● Practical Issues on Reserves
  ■ Use sufficient data to make appropriate estimates (18-24 months).
  ■ The equation does not really matter — use the DIAGNOSTICS!
  ■ Reserves estimation must become more diagnostic (less analogs).

● Take-Aways on Reserves
  ■ Reserves are defined by stimulation, geology, and fluid type.
  ■ There are no clear alternatives to the multi-fracture horizontal well.
  ■ You must use diagnostics (not statistics) to define reserves.
Summary: Reservoir Engineering

● Where we want to be: (or so we think)
  ■ Fit for purpose stimulation (... oil/gas/condensate/geology)
  ■ More effective reservoir monitoring (... this is important!)
  ■ Early EUR (... prediction/correlation?)
  ■ Well Spacing (... geology + PVT + modeling)

● How do we get there...
  ■ Better understanding of flowback/dewatering (... optimization)
  ■ Pressure-dependent properties... (... $k$, $F_{CD}$, desorption?)
  ■ Understanding of the pore-scale (... what flows when/how)
  ■ Petrophysics (... conventional petrophysics not adequate)
  ■ PVT (... oil/gas/condensate/water — HP/HT)

● Facts of life...
  ■ Analogs (... need to understand uncertainty (very high))
  ■ IP (... may be uncorrelated with EUR)
  ■ Early Productivity (... poor wells don't get better)
  ■ Time-Rate Analysis (... not representative? (chaotic operations))
Challenge Points: "What Keeps Me Up at Night…"

● What we **REALLY** know…
  ■ Tight gas is relatively easy (… vertical wells, HP/HT, PVT)
  ■ Gas shales are technically viable as a resource (… economics?)
  ■ Horizontal multi-fractured wells (… (now) taken for granted)

● What we **THINK** know…
  ■ The fracture geometry is (… planar? complex? who cares?)
  ■ The phase behavior (… can be extremely complex)
  ■ The $p_{tf}$ to $p_{wf}$ conversion(s) (… early-time heavy water load?)

● What we may **NEVER** know…
  ■ Distribution of natural fractures (… impossible?)
  ■ Transport of gas/liquids in shales (… via organic matter?)

● What we **SHOULD KNOW** in the near future…
  ■ Duration of data required for EUR (… more is always better)
  ■ Better understanding of phase behavior (… not "conventional")
  ■ Optimal well spacing/orientation/placement (… do this early!)
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End of Presentation

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