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Well completion design

Current use of simulation

- Simulation is already part of the completion design process. However, it is generally not applied effectively and the value it can provide is generally never realized:
  - Legacy completion simulation software still used in the industry today has not evolved with the advancement of simulation technology;
  - Simulation is usually applied too late in the well and completion design process. At most, service companies will use simulation to evaluate the string design just before the completion job is executed and to explore simple structural changes when risk of mechanical failure is flagged;
  - Simulation is never used as an integrated part of the design process in optimizing the string for the ultimate purpose of maximizing well productivity.

Well completion design

Motivation for improving the process

- Applying advanced simulation enables us to understand the fluid and structural dynamics generated during the completion event:
  - Understanding the pressure dynamics and leveraging the factors that influence them enables the string design to be optimized for the purpose of maximizing cleanout efficiency and, ultimately, productivity;
  - Early optimization of the design also opens up opportunities for cost reduction through the optimal selection of tools. This is something that is practically impossible to do with the legacy simulation tools still employed today;
  - Using simulation to verify the string design before the optimized completion job is run is key in managing risk of failure and the associated financial risk.
  - Driving the design and optimization process internally ensures that Tullow protects its interests and controls the decisions from a position of knowledge.

Well completion optimization

Case study

- Demonstrate potential of integrated simulation through a case study.
  - Hypothetical, short horizontal well with 4 fully loaded 7-inch guns, perforated with approximately 320 psi overbalance on a reservoir pressure of approximately 5500 psi. These conditions are typical of the Jubilee field.
  - Baseline system: 16-ft, 7-inch 12 SPF guns, HMX Millennium DP 39g charges.
- Goal: Optimize perforation string design with respect only to the effects of
  - charge loading density and
  - free volume

to maximize cleanout, minimize skin and maximize initial productivity.

Well completion optimization

Test string and matrix

- General completion string schematic:

*Spacers are always present and are activated/deactivated by allowing or preventing fluid/gas to flow into them from the guns. This ensures strings are compared on an equal basis.

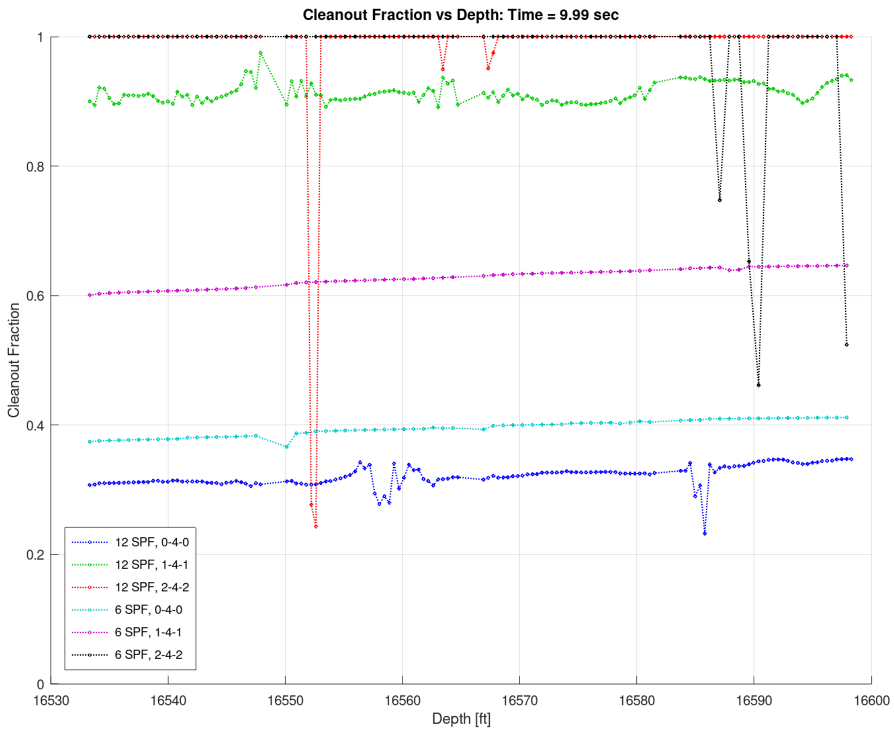
- Test matrix:

	Gun loading	Spacer/s	Guns	Spacer/s
	6 SPF	0	4	0
	6 SPF	1	4	1
	6 SPF	2	4	2
Baseline →	12 SPF	0	4	0
	12 SPF	1	4	1
	12 SPF	2	4	2

Maximize communication

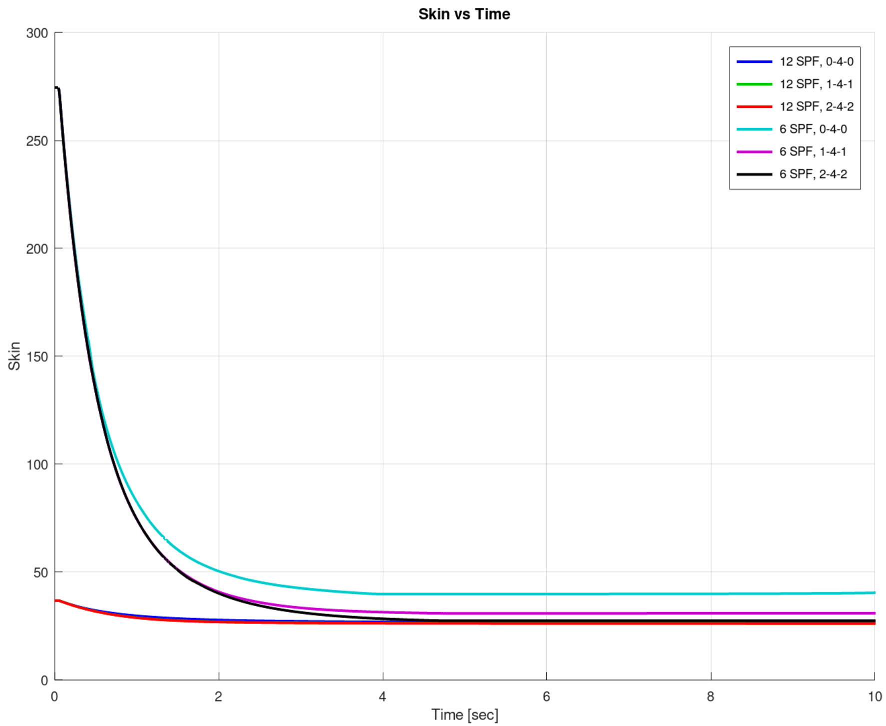
Perforation cleanout vs depth

- Two variables are evaluated for their ability to influence cleanout efficiency:
  - Gun loading density - Affects gun pressure and rate at which fluid flows into guns to pull down annulus pressure;
  - Free volume - Spacers either side of completion interval can be used to extend duration of underbalance.
- Maximum cleanout achieved with:
  - 12 SPF, 2 spacers either side of completion interval;
  - 6 SPF, 2 spacers either side of completion interval.



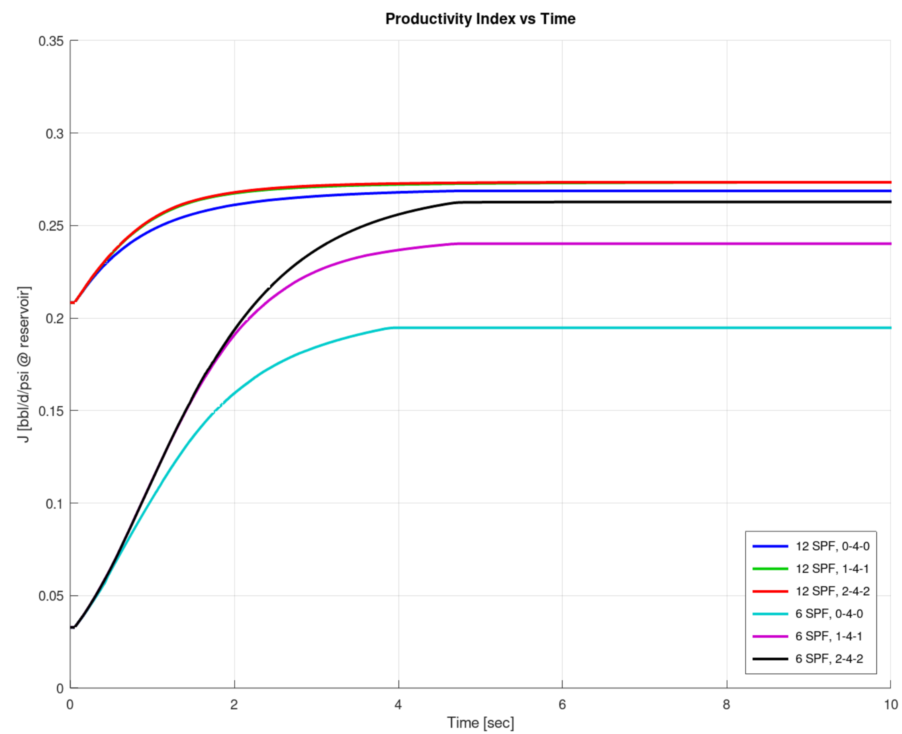
Minimize skin
Well skin vs time

- Well skin reduces as cleanout progresses in time.
- Cleanout continues to take place as long as the flow velocity through the perforations exceeds a critical threshold. Well skin decreases.
- Lower shot density guns begin at a higher skin value but drop quickly once flow begins. Higher free volume results in bigger pressure differences that clean out relatively much more effectively.
- Finally, a 6 SPF string with 2 spacers either side of the interval delivers a well skin value that is similar to the 12 SPF baseline system with no spacers.



Optimize production
Well productivity index (PI)

- Ultimately, it is maximization of well productivity that is of interest.
- The 12 SPF systems reach a final cleanout, skin and PI state sooner because of higher gun internal pressure. This results in flow slowing sooner than in the 6 SPF systems.
- Lower shot density without use of free volume (spacers) results in higher skin and a significantly lower PI.
- Half the shot density with the use of 2 spacers either side extends cleanout sufficiently to achieve a well PI similar to that of the 12 SPF baseline.
- Adding 2 spacers to the 12 SPF system maximizes the PI. Adding 4 spacers does not make a further significant difference.



Projected well productivity

Observations

- At a production pressure of 1000 psi, the baseline 12 SPF string produces 269 bbl/d. This can be improved to a maximum of 273 bbl/d by adding spacers to extend the duration of underbalance.
- The 6 SPF, 4 spacer string produces 263 bbl/d, -2.2% of the baseline and -3.7% of the maximum.
- In this case, the maximum PI can be achieved with 12 SPF and a spacer either side of the completion interval. Adding more spacers does not increase the well PI.

Configuration	Prod. Index [bbl/d/psi]	Prod. @1 ksi [bbl/d]	Indicative hardware cost*	Indicative revenue/day**
6 SPF, 0 spacers	0.1948	195	24,000	9,750
6 SPF, 2 spacers	0.2403	240	24,400	12,000
6 SPF, 4 spacers	0.2628	263	24,800	13,150
12 SPF, 0 spacers	0.2688	269	44,000	13,450
12 SPF, 2 spacers	0.2734	273	44,400	13,650
12 SPF, 4 spacers	0.2734	273	44,800	13,650

* Assumed costs: Gun tube: USD 1,000; full charge load 12 SPF: USD 10,000; full charge load 6 SPF: USD 5,000; spacer tube: USD 200.
** Assumed price per bbl: USD 50.

Well completion optimization

Test case conclusions

- From the table on the preceding slide:
  - If the design goal is to simply maximize the PI then the best configuration is the 12 SPF system with a single spacer inserted either side of the perforated interval.
  - If the design goal is to minimize the payback period then the best configuration is the 6 SPF system with two spacers inserted either side of the perforated interval.

- This example uses a very simple setup with a simple exploration of just two variables. More complex and longer completions offer significantly more opportunity for design optimization. Examples of optimization opportunities and variables include:
  - Shot density
  - Gun size
  - Internal spacer flow rate
  - Phasing
  - Charge type
  - Spacer volume
  - External spacer flow rate
  - Distribution of free volume
  - Charge size
  - Initial pressure
  - Customized local reservoir zone characteristics

- Ultimately, improving the connectivity of a well even by just a few percentage points over the baseline carries potential additional oil production revenue running into the millions of Dollars.

Extrapolation to the real world

Examples of lessons learned from Jubilee

- Simulations we have conducted in the past on long wells have shown us that the dynamic response of the system can be leveraged to improve well connectivity. Just considering the intelligent use of spacers we know that:
  - Wellbore fluid flowing into spacers helps to extend the period and increase the underbalance achieved during perforation. This can be used to optimize the overall depth and duration of underbalance during the perforation process provided sufficient volume is made available.
  - Perforations in the vicinity of spacers or in short intervals tend to achieve better dynamic underbalance than those in the middle of long intervals. This is due to the local drop in pressure experienced as fluid is allowed to move from the wellbore, through the guns and into the spacers.
  - The rate at which spacers fill can be influenced and optimized to shape the duration and extent of underbalance, for example through the design of the tandem couplings or introducing vented spacers into the interval, or through their individual placement.
  - Intelligent use of free volume can be made to create a completion with much more effective communication to the formation than is generally the norm. Even today, this aspect of completion design is not being effectively leveraged.

Well completion optimization
Leveraging the value of simulation

- How do we leverage the value?
  - Conduct design optimization early in the project for biggest impact in reducing perforation cost and maximizing future production.
  - Run simulation before the well completion job to manage risk and estimate expected communication with optimized design in actual completion configuration and formation. Perform final design optimization tweaks.
  - Calibrate the simulation after the completion job is run to gain insight, learn and improve the practice on future jobs.
- Ultimate expectations:
  - **Reduced completion cost;**
  - **Reduced technical risk;**
  - **Increased productivity.**
- Stakeholders:
  - Well engineering team;
  - Subsurface team;
  - Shareholders.

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