TWENTIETH SPE IMPROVED OIL RECOVERY CONFERENCE
IOR 2016
NEW CHALLENGES, NEW SOLUTIONS

9–13 April 2016
COX BUSINESS CENTER
Tulsa, Oklahoma, USA

SPE 179615-MS

Field Test Results of a New Silicate Gel System that is Effective in Carbon Dioxide Enhanced Recovery and Waterfloods

Kenneth D. Oglesby, Impact Technologies LLC ; David D'Souza, Denbury Resources;
Chad Roller, PhD, and Ryan Logsden, MidCon-Energy Partners LP;
Lyle D. Burns, Clean Tech Innovations LLC; Betty J. Felber, PhD, EOR Consultant

SPE International
Society of Petroleum Engineers

Field Test Results of a New Silicate Gel System that is Effective in Carbon Dioxide Enhanced Recovery and Waterfloods

What New Silicate Gel System?

- Multiple component system with Silicate-Polymer-Initiator+ (SPI)
- Highly flexible / adaptive for variety of conditions/ applications
- Water-like up to high viscosity when pumped
- Initiators- external (positional, CO_2) or internal (time / temp)
- Soft reform-able to very Hard ringing, true gels, set ‘toe to heel’
- Use of leak-off control additives possible
- High Temperature stable > 392^{o}F (short tests to 479^{o}F)
- Environmentally Friendly

Field Test Results of a New Silicate Gel System that is Effective in Carbon Dioxide Enhanced Recovery and Waterfloods

Presentation Summary

1) **Laboratory Testing** of new Silicate-Polymer-Initiator (SPI) Gel System-Beaker, Penetrometer, Extrusion, Dynamic Flow Pack testing

2) **Treatment Optimization Options**

a. Low vs high viscosity & strength (toe to heel) treatment fluids
b. One large volume treatment vs multiple smaller treatments

3) **Field Case Histories-**

a. Denbury Resources, c-Mississippi, fractured sandstone, CO_2 Fld
b. w-Texas, San Andres matrix dolomite, mature CO_2 WAG Flood
c. Mid-Con Partners, c-Oklahoma, matrix sandstone, waterflood

Field Test Results of a New Silicate Gel System that is Effective in Carbon Dioxide Enhanced Recovery and Waterfloods

History of Conformance in the Oilfield

Purpose: ***Improve process efficiency- more ultimate oil- lower LOE!***
in EOR (waterflood, CO_2), geothermal, primary production and drilling.

Methods: *Mechanical barriers* - wood, packers, liners, etc- inside wellbore.
Also - cements, barite, bentonite- only slightly deeper.

Chemical barriers-
1922 *Acid Silicate systems* original conformance chemical, fast reactions, rigid, non-uniform and brittle precipitates.

1970's *cross-linked Polyacrylamides* (PAMs) with Cr^{6+} heavy metal initiators. Various PAMs types and initiators improved that process.

Field Test Results of a New Silicate Gel System that is Effective in Carbon Dioxide Enhanced Recovery and Waterfloods

Conformance History- *continued*

Biggest problem with cross-linked polyacrylamide (xl-PAM) systems is- inability to retard reaction and maintain strength.

Biggest problem with prior silicate systems was- inability to retard reaction and provide elasticity.

New SPI system overcomes those barriers.

In addition, silicate systems known for high temperature capabilities. High pH amorphous liquid glass systems are mostly used now.

Field Test Results of a New Silicate Gel System that is Effective in Carbon Dioxide Enhanced Recovery and Waterfloods

SPI Gel Development History

- 2005-2008 US DOE/ PSU Stripper Well Consortium grants for initial SPI chemical system development.
- 2006-2008 OCAST grants for casing repairs and basement sealing.
- Laboratory testing at RTA Systems Laboratory and TORP at KU.
- 2008 **SPE No.113490** by Burns, et. al. on SPI lab work
- 2009 DOE SBIR Phase I for internal initiator development.
- 2011-2014 DOE DE-FE0005958 for **CO_2 Field Testing**.
- 2011-2015 DOE DE-EE0005508 **high temp geothermal (to 479ºF)**.
- 2014 **US patent #882238** issued with other US & Int'l pendings.
- 2016 **SPE No.79615MS** by Oglesby, et. al. on field case histories

Field Test Results of a New Silicate Gel System that is Effective in Carbon Dioxide Enhanced Recovery and Waterfloods

SPI Gel Laboratory Testing

- Brookfield Viscosity- ***near water at reservoir temps***,
  7.5 cp at low conc. / 11.5 cp at med-high conc. (70^{o}F, 12 rpm)
- Densities- 1.02 (low conc.) to 1.07 Sp. Gr. (high conc.)
- Penetrometer (ASTM D-217-68)- **2 to 48X stronger> 20kppm xl-PAM**
- Bulk Gel Shear Tests (BGST, SPE 13567)- *could not extrude med-high concentration SPI gels.* Low conc. SPI gels were **2 to 4.5X stronger than highest conc. xl-PAMs.**
- Dynamic Flow Tests- crushed & sorted Sandpack & Dolomite

Field Test Results of a New Silicate Gel System that is Effective in Carbon Dioxide Enhanced Recovery and Waterfloods

SPI Gel Laboratory - Bulk Gel Shear Tests (BGST, SPE 13567)

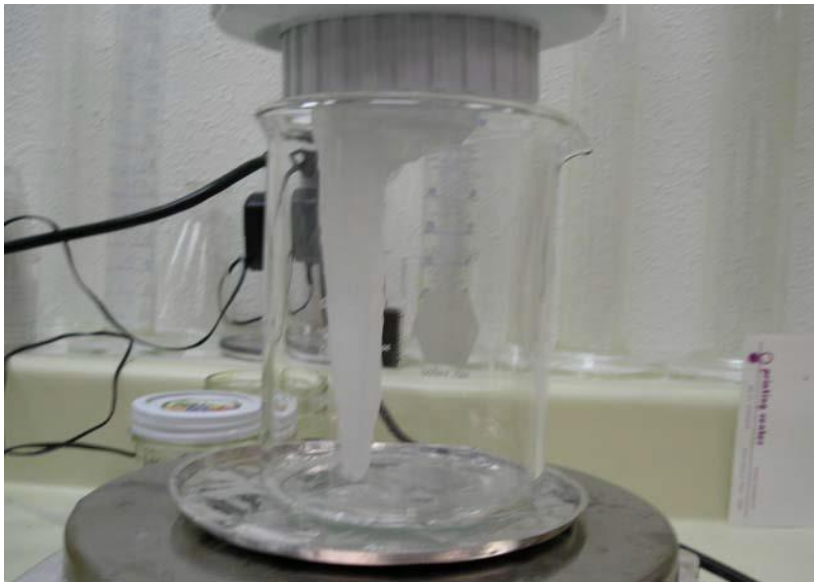
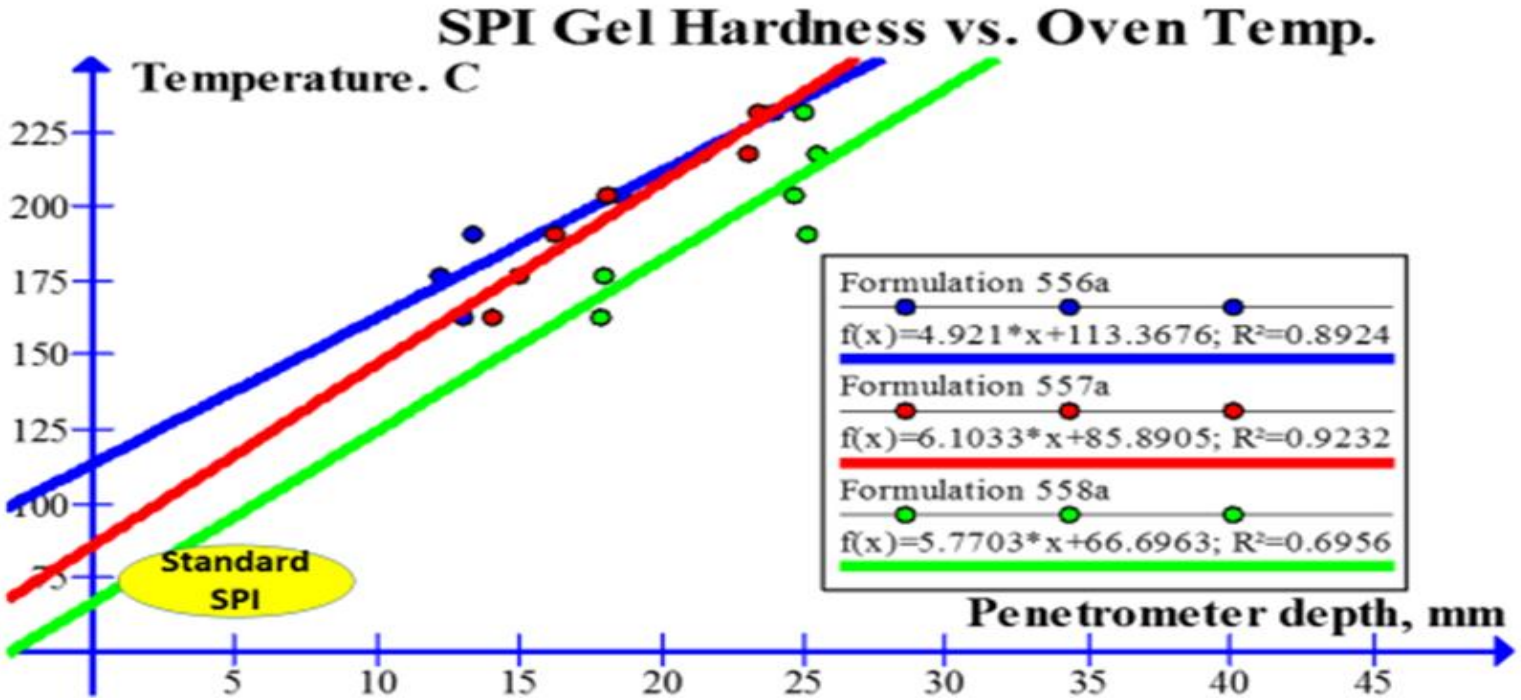


Figure 1. PAM cross-linked with Aluminum-Citrate tested through BGST

Figure 2. New Silicate Gel through BGST and partially reformed

Field Test Results of a New Silicate Gel System that is Effective in Carbon Dioxide Enhanced Recovery and Waterfloods

SPI Gel Laboratory – High Temperature Testing to 437°F/ 225°C



Field Test Results of a New Silicate Gel System that is Effective in Carbon Dioxide Enhanced Recovery and Waterfloods

SPI Gel Laboratory Dynamic Flow Tests- Sandpack Field A Sandstone

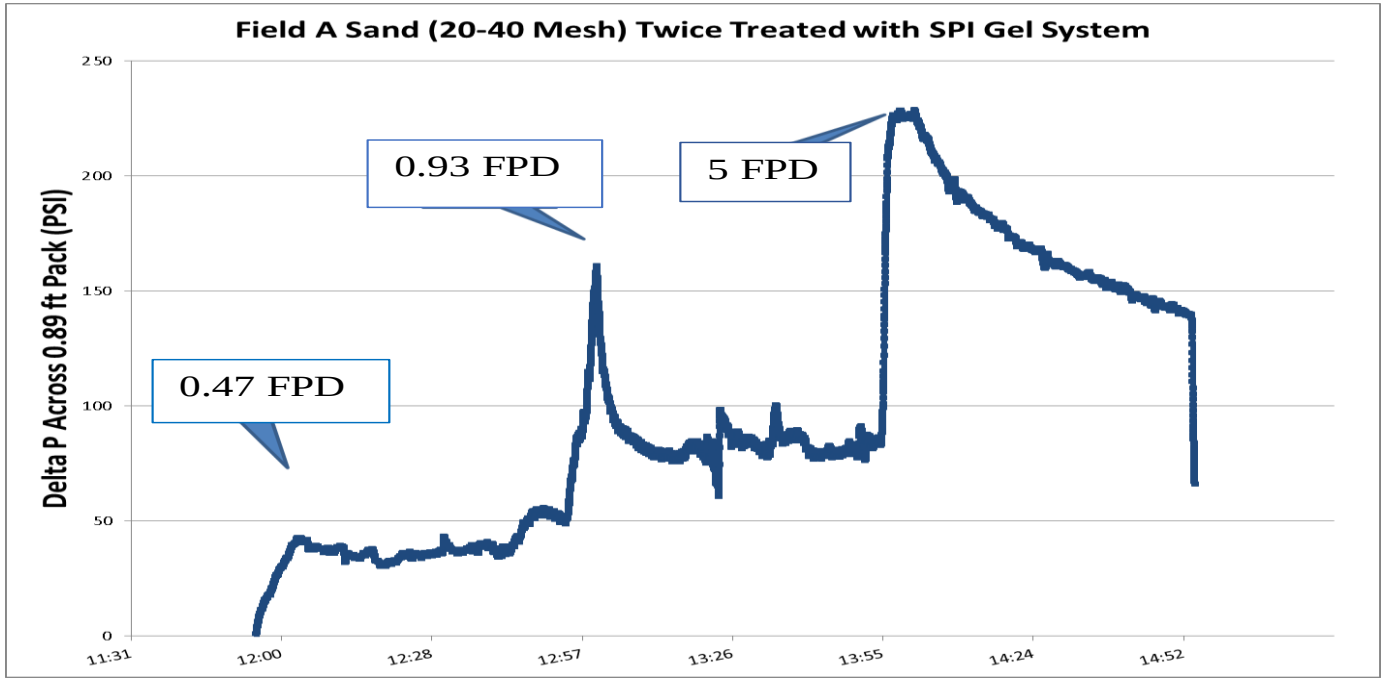


Figure 3. Water Injectivity Tests in a Sandpack with Denbury Field A's sandstone core material after two Silicate Treatments [63]

Field Test Results of a New Silicate Gel System that is Effective in Carbon Dioxide Enhanced Recovery and Waterfloods

SPI Gel Laboratory Dynamic Flow Tests- Sandpack Field A sandstone

Table 3. Sandpack Injectivity Testing comparing New Silicate Gel treatments in Ottawa Sand and Denbury Field A Sandstone core material [63]

	Sandpack			Denbury Field A Sand		
	Without Treatment	1st Treatment	2nd Treatment	Without Treatment	1st Treatment	2nd Treatment
A, ft^2	5.45E-03	5E-03	5E-03	5.45E-03	5E-03	5E-03
ΔX, 1 ft	1	1	1	1	1	1
Q [cc/min]	0.1	0.1	0.1	0.1	0.1	0.1
Q [bbl/day]	9E-04	9E-04	9E-04	9E-04	9E-04	9E-04
ΔP [psi]	0.2	18	90	0.7	30.6	86
μ = visc of water [cp]	1	1	1	1	1	1
K [md]	737	8	2	211	5	2
F_{krr}		90	450		44	123

Field Test Results of a New Silicate Gel System that is Effective in Carbon Dioxide Enhanced Recovery and Waterfloods

SPI Gel Laboratory Dynamic Flow Tests- Field B San Andres dolomite

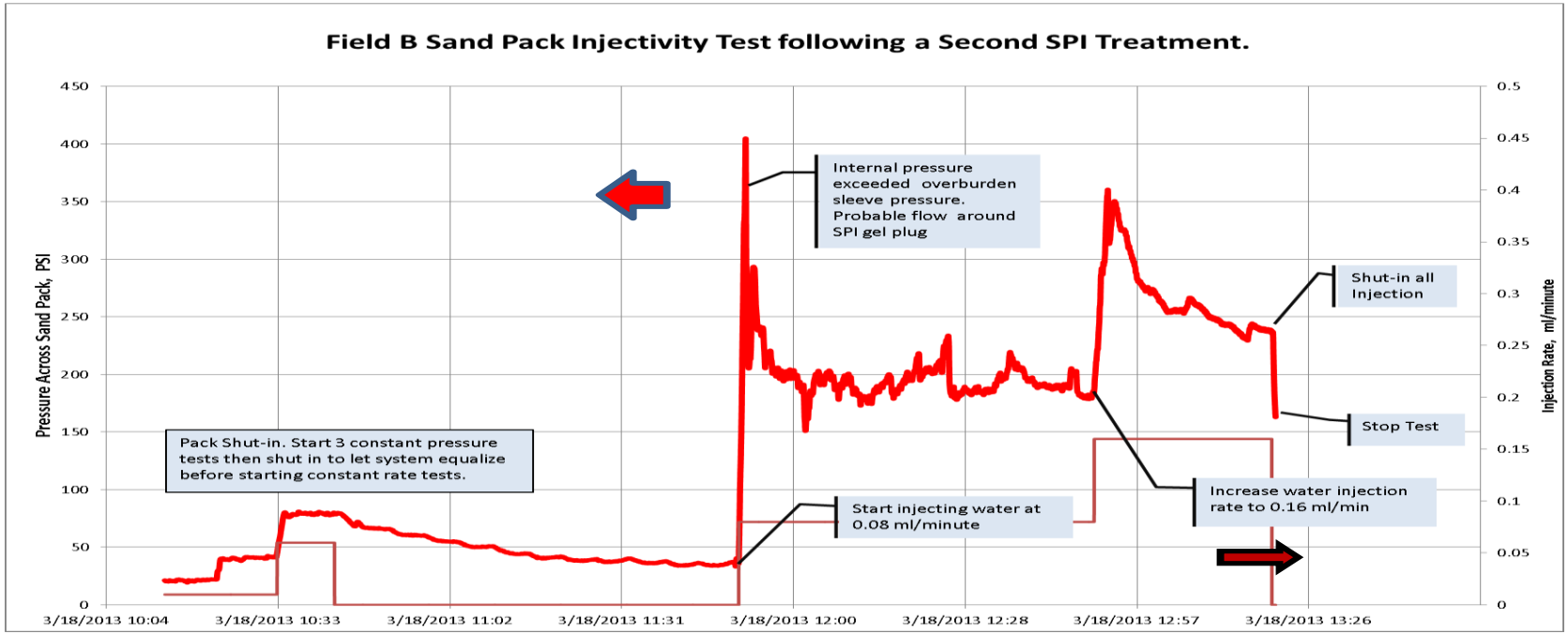


Figure 4. Water Injectivity following 2nd Silicate Treatment in a Field B San Andres Dolomite Pack with early Constant Pressure Period before Constant Rate [63]

Field Test Results of a New Silicate Gel System that is Effective in Carbon Dioxide Enhanced Recovery and Waterfloods

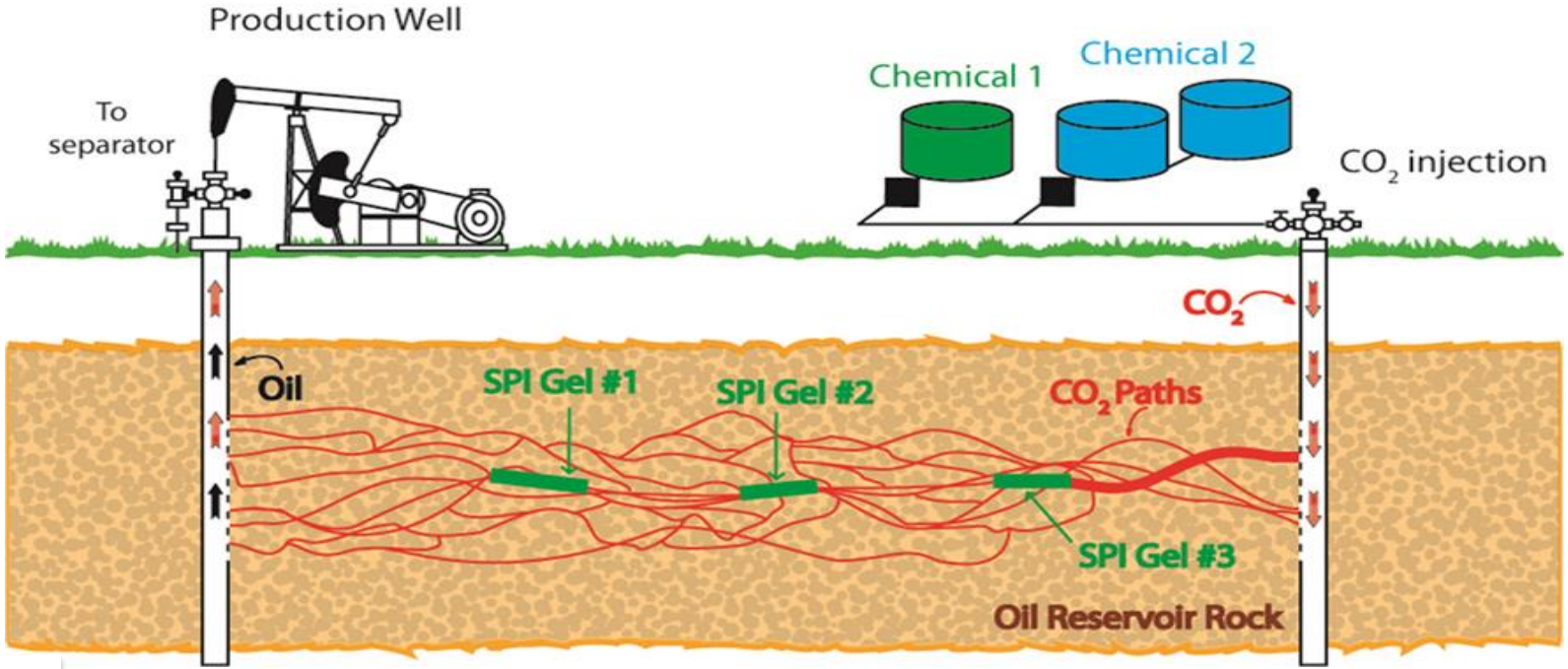
SPI Gel Laboratory Dynamic Flow Tests- Field B San Andres dolomite

Table 4. Field B San Andres Dolomite Pack Water Injectivity Tests with one and two Silicate Treatments [63]

	Crushed and Sieved Field B San Andres Dolomite, 20-40 Mesh		
	Water Calibration	1st SPI Treatment	2nd SPI Treatment
A, ft^2	1.23E-02	1.23E-02	1.23E-02
ΔX, 1 ft	0.89	0.89	0.89
Q [cc/min]	0.12	0.12	0.12
Full Bore Velocity, fpd	0.50	0.50	0.50
Interstitial Velocity, fpd	1.1	1.1	1.1
μ = visc of water [cp]	1	1	1
ΔP [psi]	0.08	3.4	194
K=permeability [md]	407	10	0.17
Residual Resistance Factor, F_{rr}		43	2425

Field Test Results of a New Silicate Gel System that is Effective in Carbon Dioxide Enhanced Recovery and Waterfloods

Optimization Options- One Large vs Multiple Small Volume Treatments



Simplified Schematic of Multiple, Smaller Treatment Volumes in a CO_2 Flood

2012-2014 SPI Field Treatment Summary

Field A Injector

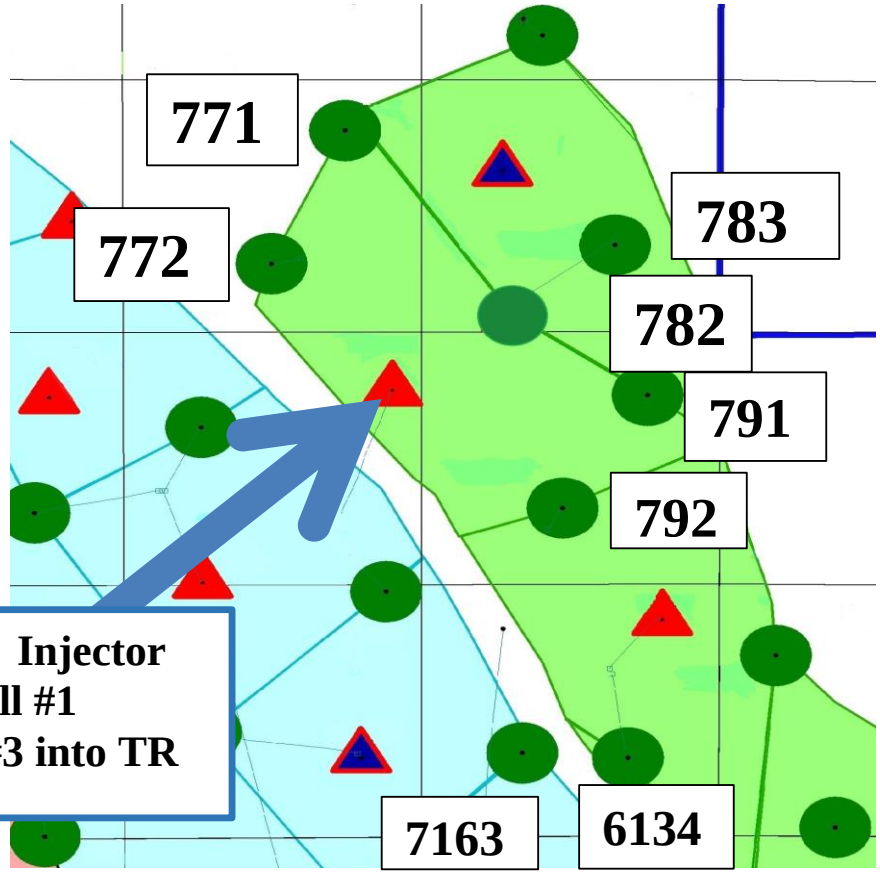
SPI #	Well #	State	Well Type	Rock Type	Depth	Pre-Treatment Status: Rate BPD MMCFPD	WHP PSIG	Injectivity Rate/PSI	Interwell Cap- BBLs	SPI Treatment: Mo/YR	BBLs	Injectivity Reduction (% of PreTrement): 3 mo.	12mo.	24 mo.
SPI1	1	cMS	INJ-CO_2	sstone	5102	11	1400	7.9	>20,000	Nov-12	950	28%	re-treated	na
SPI3	1	cMS	INJ-CO_2	sstone	5102	8.26	1500	6.0	>20,000	Feb-13	3842	57%		
											4792		*CO2 Overall*	58%

Field A Producer

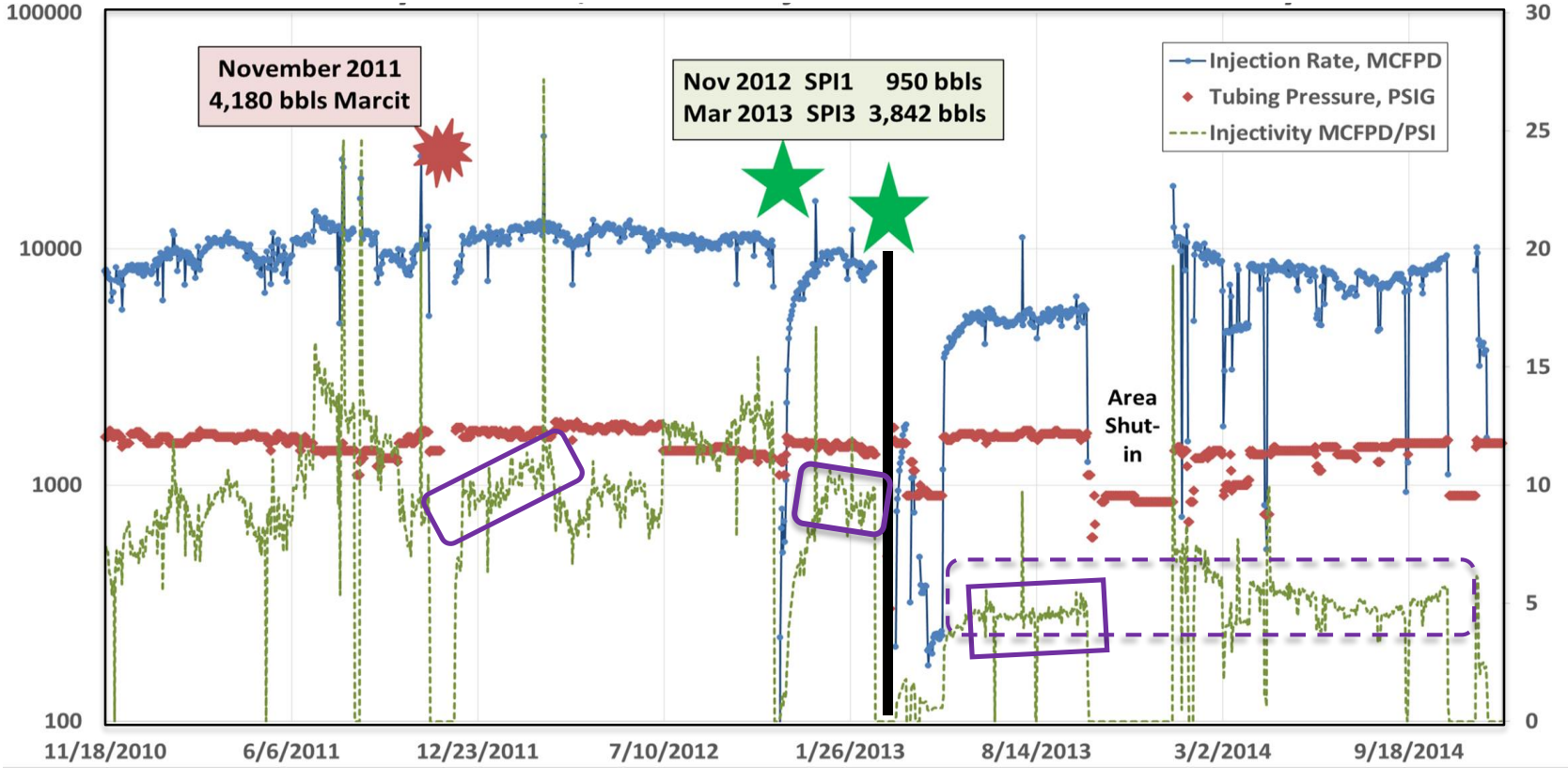
SPI #	Well #	State	Well Type	Rock Type	Depth	Pre-Treatment Status: Oil BOPD	GOR MSCF/BBL	Oil Trend	GOR Trend	SPI Treatment Size- BBLs	cum Oil BBLs over Prior Trend / GOR Change over Last Prior: 3 mo.	12 mo.	24 mo.
SPI2	2	cMS	PROD	sstone	5102	20	450	-78%/yr	+700%/yr	4349	-	750	6,600
			CO_2 Flood	*Well Shut-in prior to treatment due to excessive GOR*							-64%	flat	flat

Field Test Results of a New Silicate Gel System that is Effective in Carbon Dioxide Enhanced Recovery and Waterfloods

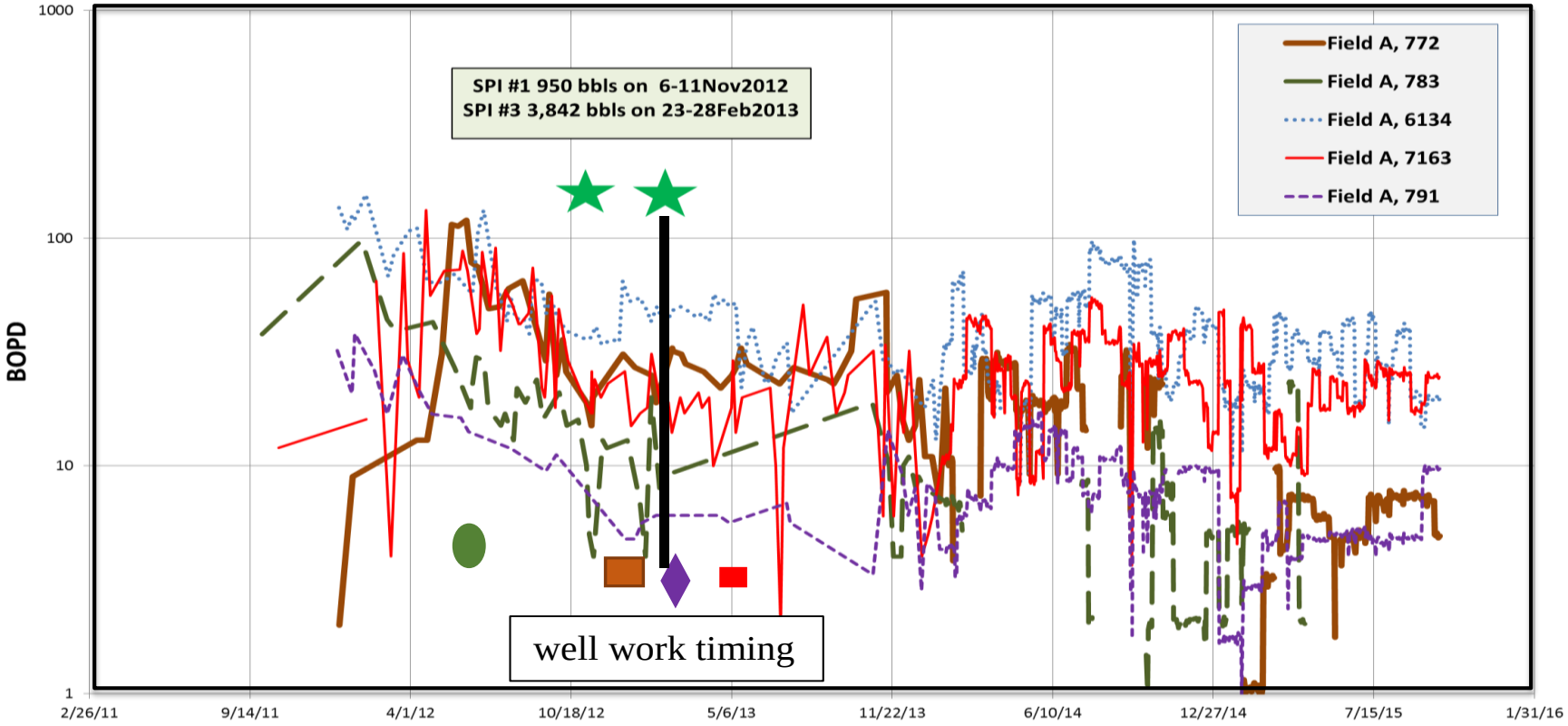
Field A
Fractured sandstone.
Well #1
Only 6 foot zone open.



Denbury Field A, Mississippi Sandstone CO_2 Flood
Well #1 Injection Rate and Pressures



Denbury central-Mississippi, Field A CO_2 Flood
Offset Production Well BOPD Responses to SPI 1& 3 Treatments



Field Test Results of a New Silicate Gel System that is Effective in Carbon Dioxide Enhanced Recovery and Waterfloods

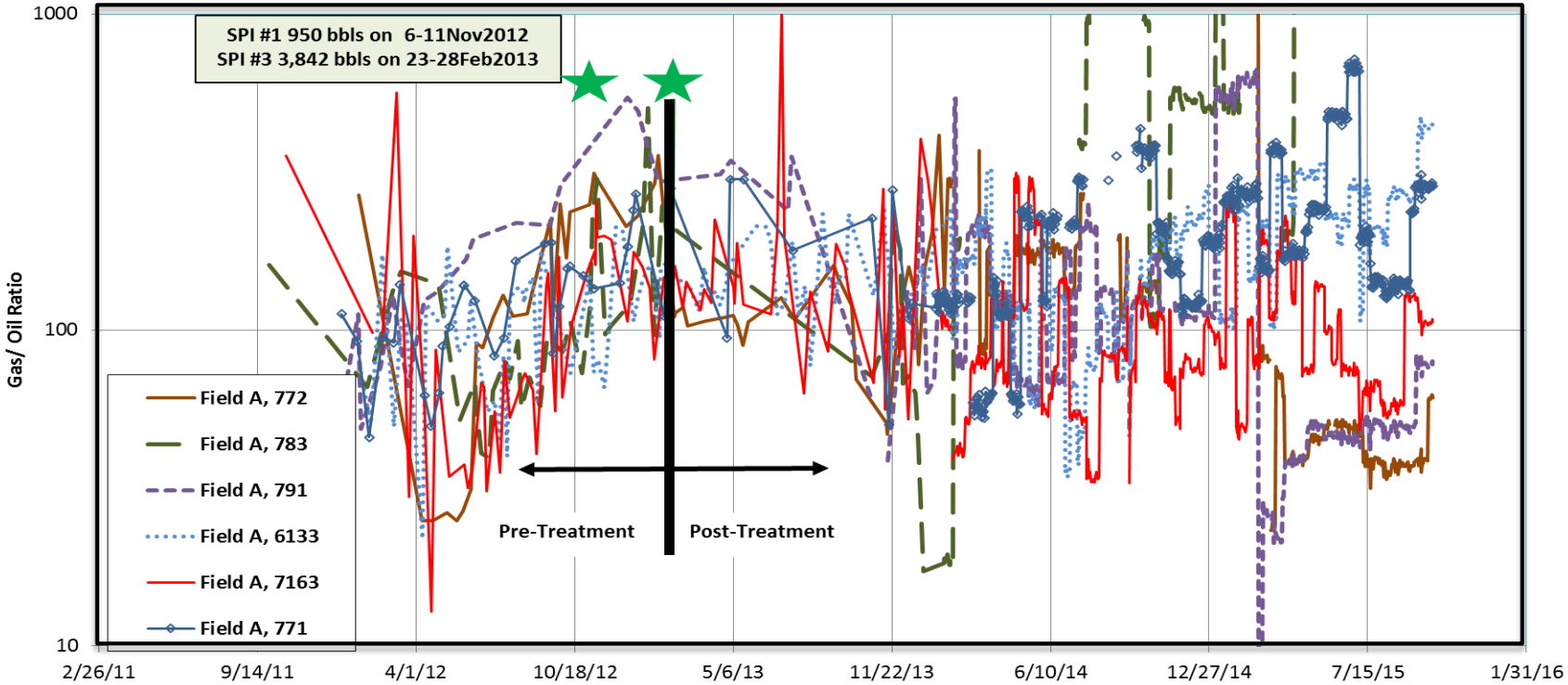


Figure 6. Field A- Selected Northern Production Wells' Gas: Oil Ratios

Field Test Results of a New Silicate Gel System that is Effective in Carbon Dioxide Enhanced Recovery and Waterfloods

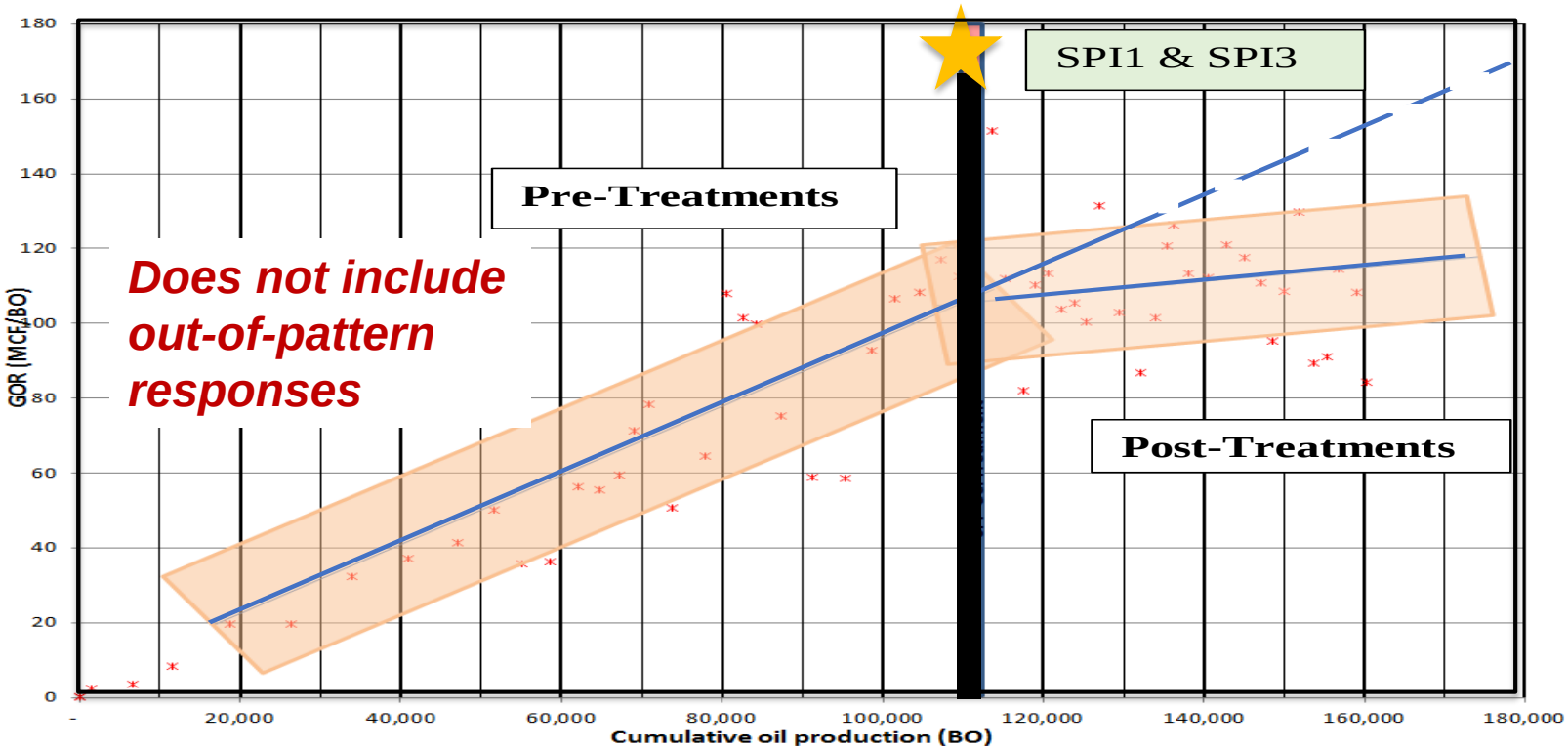


Figure 7. Field A, Well #1 Pattern Analysis Plot- GOR vs Cum Oil Prod

Field Test Results of a New Silicate Gel System that is Effective in Carbon Dioxide Enhanced Recovery and Waterfloods

Field A

Well #2, top of structure.
Shut-in previously due to excessive GOR.
Reactivated for treatment.

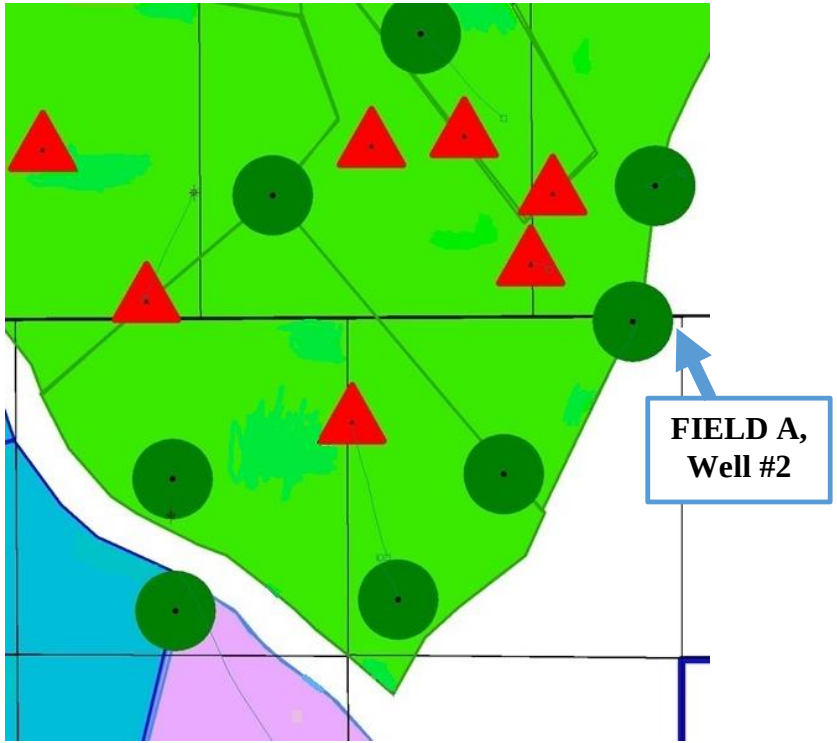
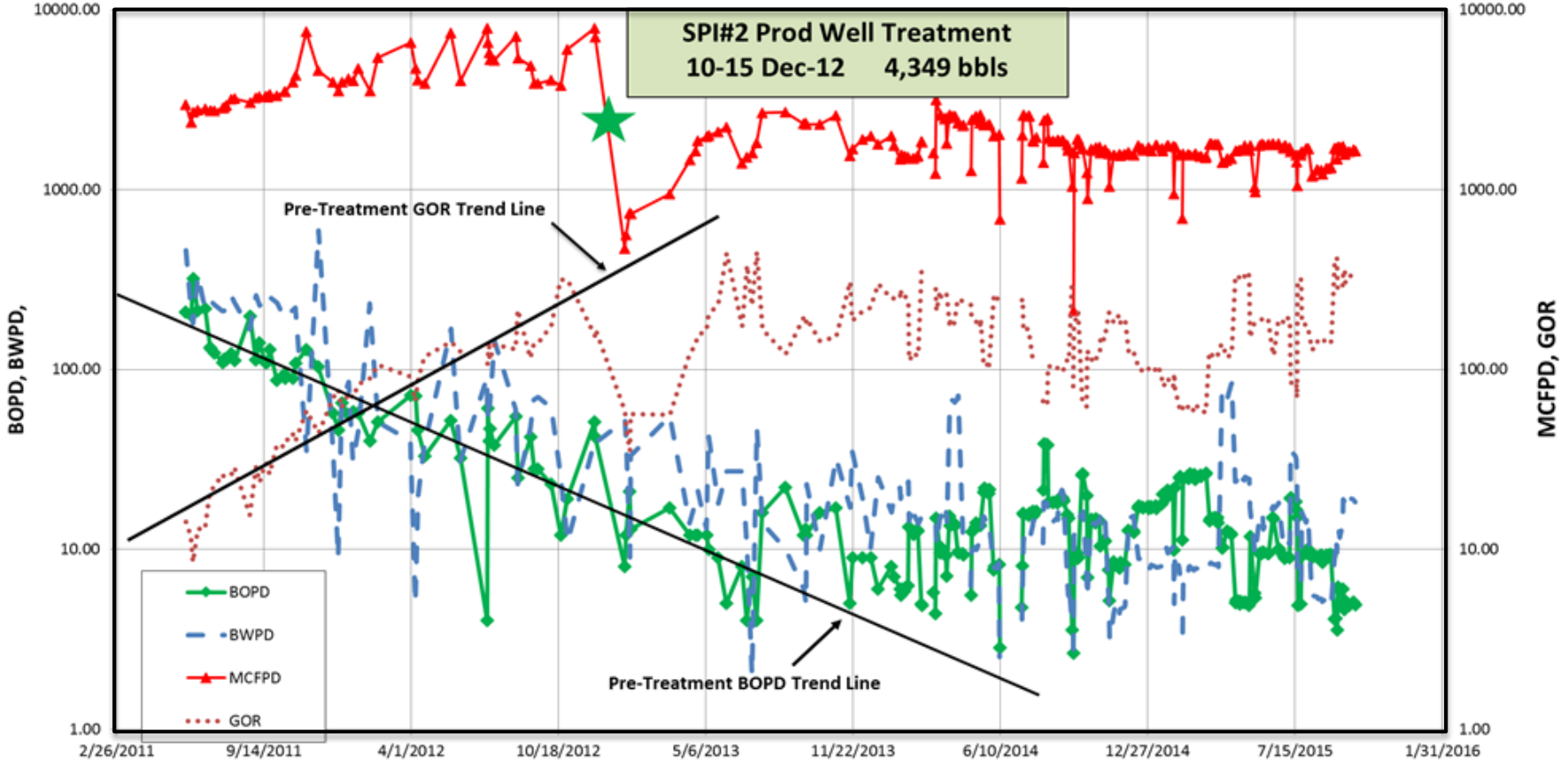


Figure 8. Denbury Field A, Map of the Southern Area showing Producer Well #2's Location near the Top of Structure.
Red Triangles are Injectors, Green Circles are Producers

Field Test Results of a New Silicate Gel System that is Effective in Carbon Dioxide Enhanced Recovery and Waterfloods



2012-2014 SPI Field Treatment Summary

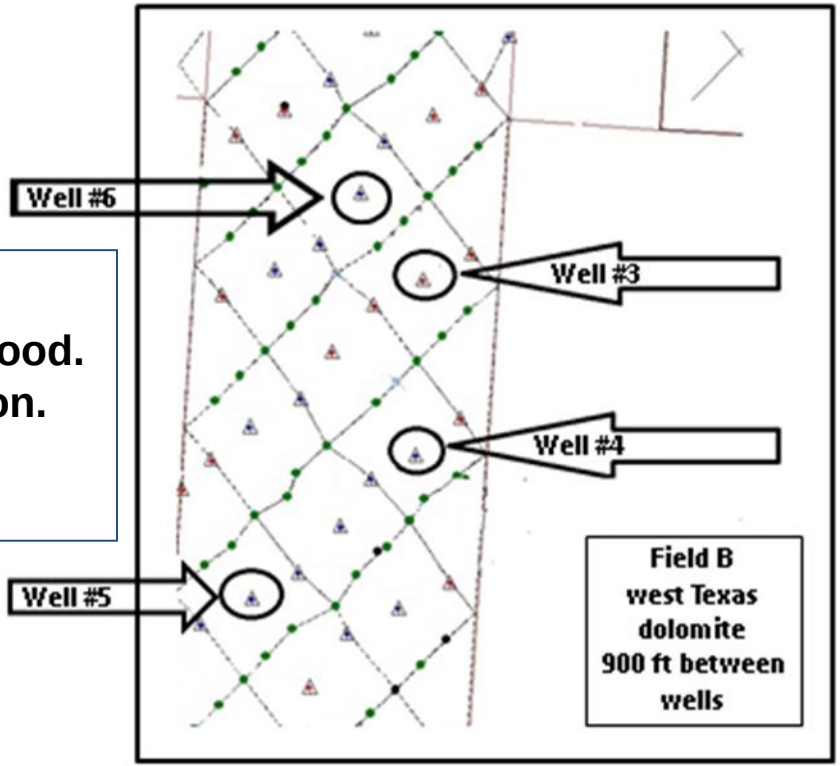
Field B Injectors

SPI #	Well #	State	Well Type	Rock Type	Depth	Pre-Treatment Status: Rate BPD MMCFPD	WHP PSIG	Injectivity Rate/PSI	Interwell Cap- BBLs	SPI Treatment: Mo/YR	BBLs	Injectivity Reduction (% of PreTrement): 3 mo.	12mo.	24 mo.
SPI4	3	wTX	INJ-CO_2-WAG	dolo	5020	1.0	2350	0.43	400	Sep-13	130	47%	re-treated	na
SPI6	3	wTX	INJ-CO_2-WAG	dolo	5020	0.5	2200	0.23	400	Sep-13	225	15%		
											355	*Overall CO2 & Water=*		*10%*
SPI5	4	wTX	INJ-CO_2-WAG	dolo	5020	0.92	2371	0.39	2800	Sep-13	705	9%	Evaluate ReTreat	
SPI8	4	wTX	INJ-CO_2-WAG	dolo	5020	0.84	2365	0.35	2800	Oct-13	0	23%		
											705	*Overall CO2 & Water= No Chg*		
SPI7	5	wTX	INJ-Water	dolo	5020	*600.0*	*1250*	*0.5*	5500	Oct-13	1029	CO2 Injectivity- NA Water Injectivity 50% lower*		
SPI9	6	wTX	INJ-CO_2-WAG	dolo	5020	1.75	2075	0.84	17500	Nov-13	3265	CO2 Injectivity- No Chg Water Injectivity- 50% lower*		

Field Test Results of a New Silicate Gel System that is Effective in Carbon Dioxide Enhanced Recovery and Waterfloods

Field B

west Texas, mature CO_2 WAG Flood.
San Andres Dolomite Formation.
All five treatments in
CO_2 -Water Injection Wells.



Field Test Results of a New Silicate Gel System that is Effective in Carbon Dioxide Enhanced Recovery and Waterfloods

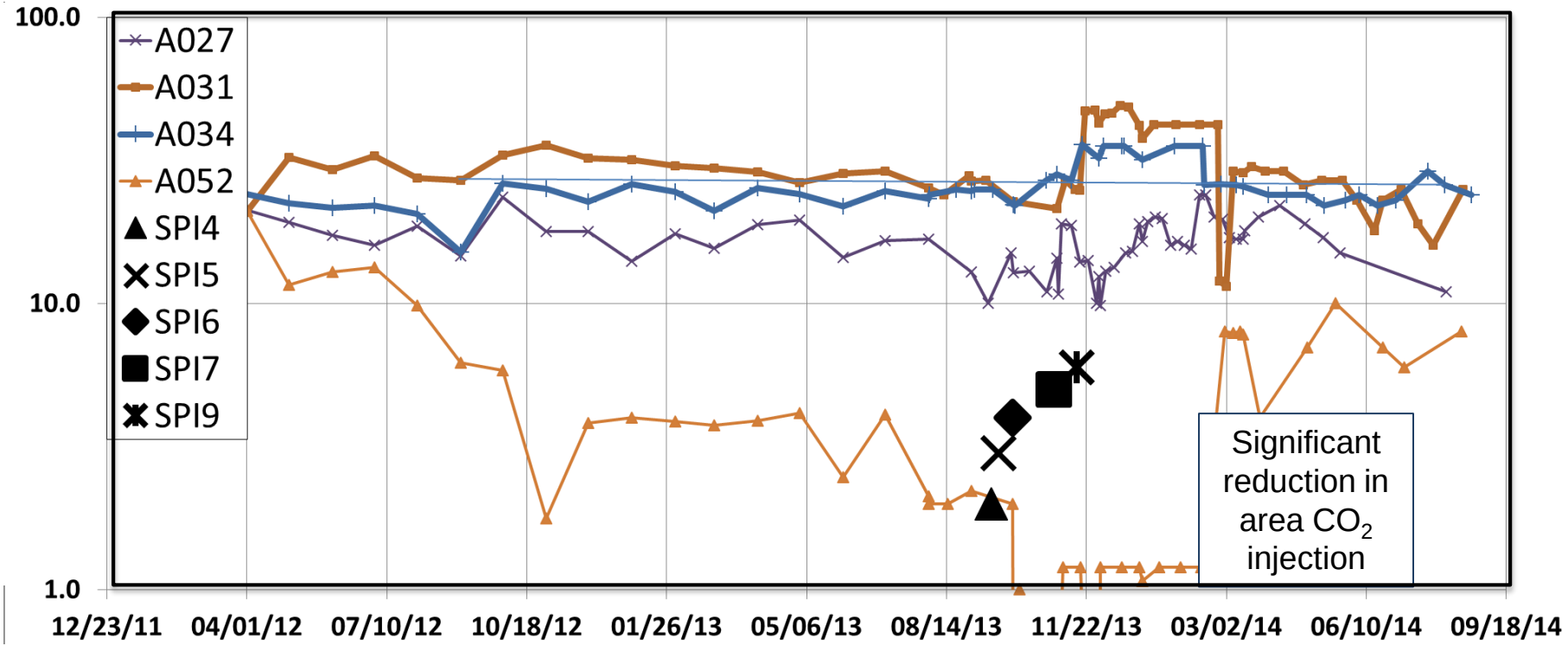


Figure 15. Field B Selected Production Well Responses, BOPD

Field Test Results of a New Silicate Gel System that is Effective in Carbon Dioxide Enhanced Recovery and Waterfloods

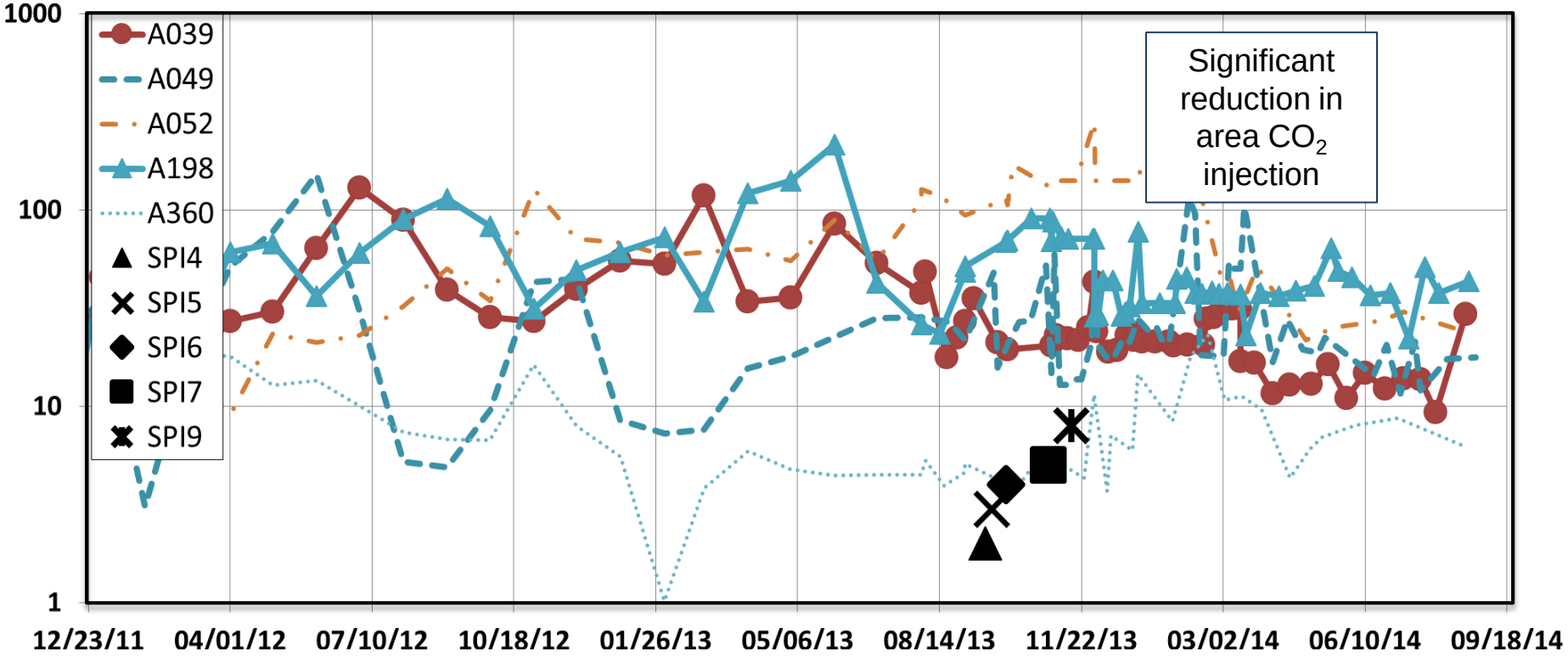


Figure 16. Field B Selected Production Well Responses, GOR

Field Test Results of a New Silicate Gel System that is Effective in Carbon Dioxide Enhanced Recovery and Waterfloods

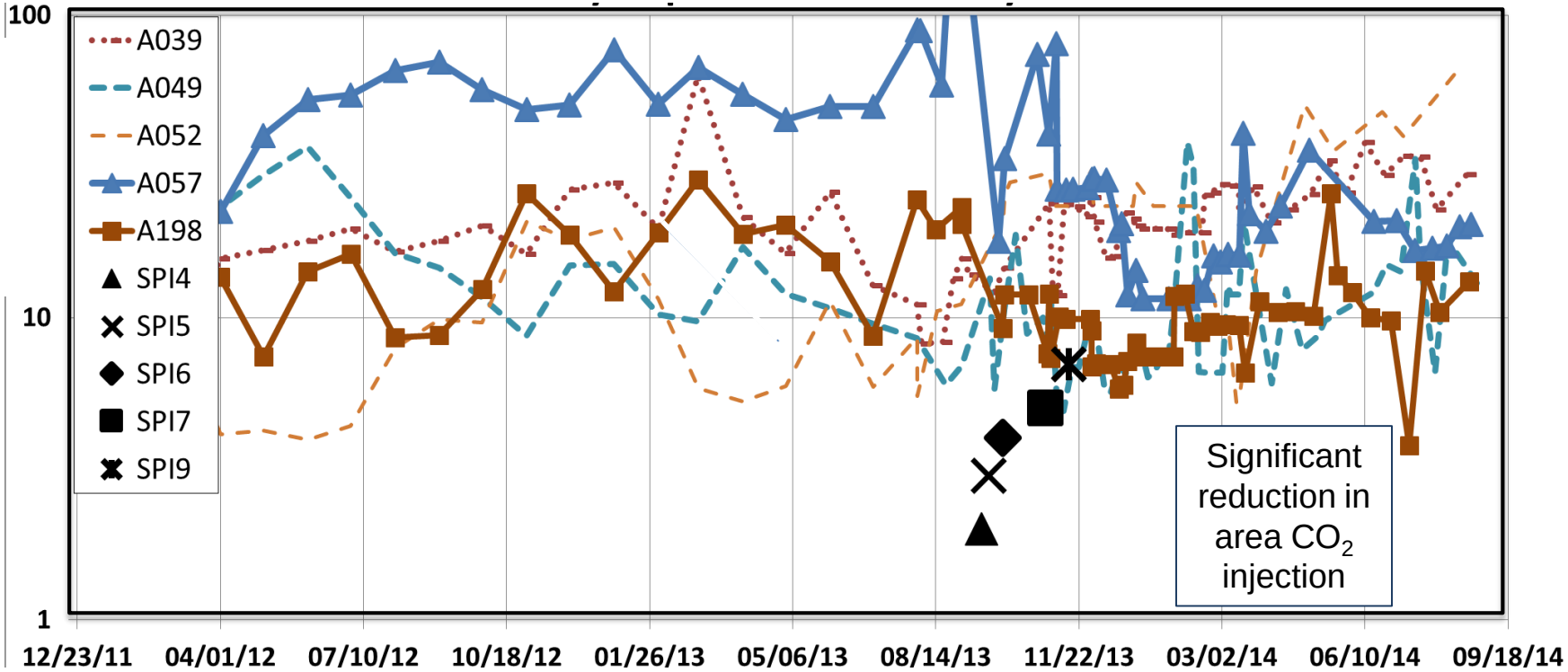


Figure 17. Field B Selected Production Well Responses, WOR

2012-2014 SPI Field Treatment Summary

Field C Injectors

SPI #	Well #	State	Well Type	Rock Type	Depth	Pre-Treatment Status: Rate BPD MMCFPD	WHP PSIG	Injectivity Rate/PSI	Interwell Cap- BBLs	SPI Treatment: Mo/YR	BBLs	Injectivity Reduction (% of PreTrement): 3 mo.	12mo.	24 mo.
SPI10	7	cOK	INJ-Water	sstone	1735	400	0	vacuum	unknown	Dec-14	200	Water Injectivity - No Chg Plugged Thief Zone		
SPI11	8	cOK	INJ-Water	sstone	1270	1375	0	vacuum	unknown	Aug-15	279	Water Injectivity - No Chg Slight Change in Profile		

Field Test Results of a New Silicate Gel System that is Effective in Carbon Dioxide Enhanced Recovery and Waterfloods

Field C
central OK
Sandstone
Waterflood
Two Injectors

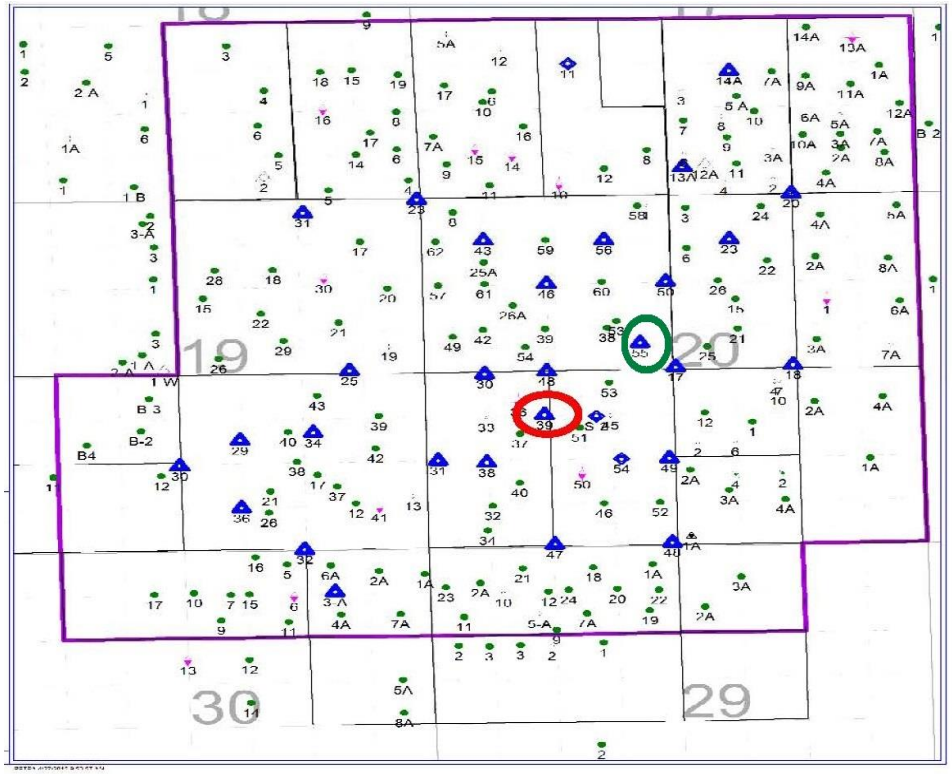


Figure 18. Central Oklahoma, Cleveland Field Map

Field Test Results of a New Silicate Gel System that is Effective in Carbon Dioxide Enhanced Recovery and Waterfloods

Mid-Con Energy - central OK Waterflood- Thief Zone

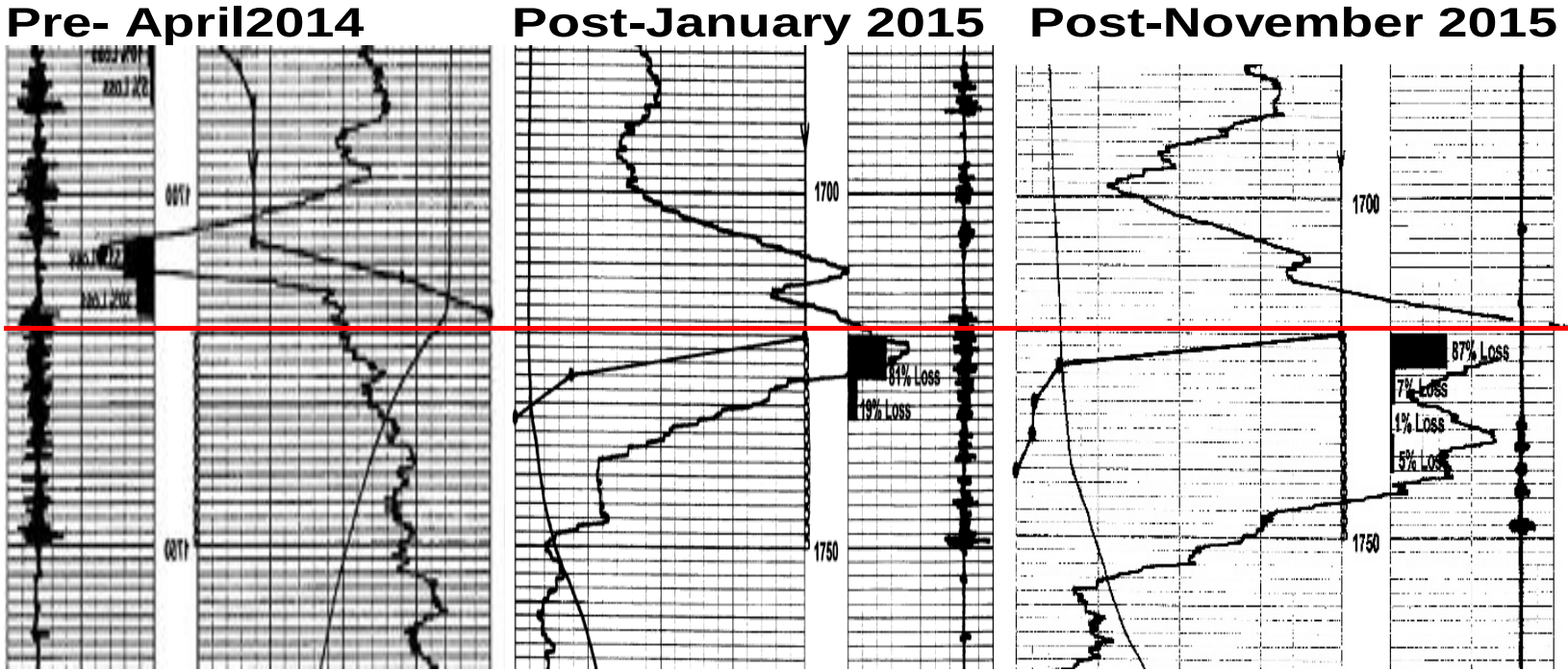


Figure 19. JA Jones #55 Pre- and Post-Treatment Injection Profile Logs.

Red line is top of perforated zone. Note- Thief Zone Plugged

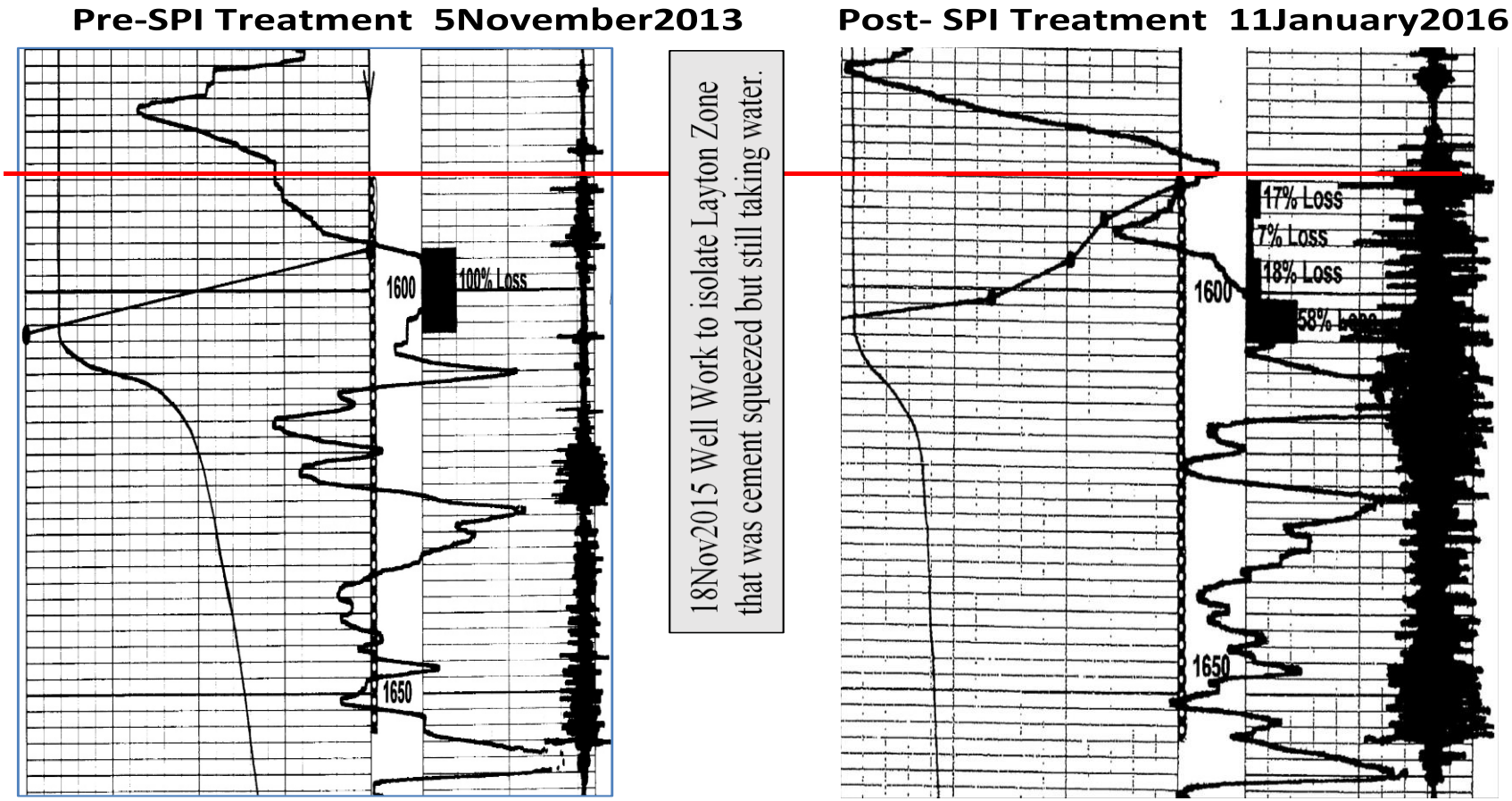


Figure 22. Mullendore & Berry #39 - Injection Profile Logs.

Note: Red Line is top of Cleveland perforations.

Field Test Results of a New Silicate Gel System that is Effective in Carbon Dioxide Enhanced Recovery and Waterfloods

Conclusions

- The **SPI Gel System**
  - Gel chemistry initiated with CO_2 - proven in the lab and field, in both dolomites and sandstones, in both injectors and producers.
  - Medium gels >> 10X stronger than any xl-PAM system and still has elasticity.
  - Gel chemistry internally initiated - tested in lab and field.
  - Both Internal and External systems can at high concentrations for strong gels placed “toe to heel”.
  - Lab tested in sand packs at 479^{o}F.

Field Test Results of a New Silicate Gel System that is Effective in Carbon Dioxide Enhanced Recovery and Waterfloods

Conclusions- continued

- Optimize Treatment -
  - Concentration – Strength, ‘Toe to Heel’
  - Viscosity- stepped flow path sealing
  - Volume - One large vs multiple smaller treatments.
  - Higher success and lower costs.

- Direct well comparisons to xl-PAM / Marcit gel treatments showed the benefits of SPI’s lower viscosity, ‘Toe-Heel’ stronger gel strength and unique initiation methods.

Field Test Results of a New Silicate Gel System that is Effective in Carbon Dioxide Enhanced Recovery and Waterfloods

Conclusions- continued

- Field A- fractured sandstone- CO_2 injection well treatments **reduced GOR trends, increased ultimate oil and impacted off-pattern producers.** ***Lower LOE*****.**
- Field A- fractured sandstone- production well test treatment **lowered gas rate and GOR.** ***Increased Ultimate Oil & Lower LOE***
- Field B- San Andres dolomite- injection well treatment outcomes **inconclusive** due to major field changes (cut CO_2 injection rates).
- Field C- matrix sandstone- waterflood injection well treatments (internal initiators) **shut-off thief zone and improved conformance**.

Acknowledgements

Many thanks to Denbury Resources, MidCon-Energy Partners LP and the anonymous west Texas operator for sharing their field data.

Many thanks for funding support from the US Department of Energy (DOE) Fossil Fuels and Energy Efficiency and Renewable Energy (EERE) geothermal programs; the Stripper Well Consortium (SWC) at Penn State University; and the Oklahoma Center for the Advancement of Science and Technology (OCAST) programs.

Much thanks to Bryan McCollam with Impact for field support.