Society of Petroleum Engineers
Annual Technical Conference
and Exhibition

27–29 October 2014
RAI CENTRE
Amsterdam, The Netherlands

SPE 170809
Long-Time Diversion in SAG Foam Enhanced Oil Recovery From Field Data

W.R. Rossen, Delft University of Technology; A. A. Ocampo-Florez, A. Restrepo, H. D. Cifuentes, J. Marin, Equión Energía Ltd

HOST ORGANISATION

SPE International

Alternate Title:

Don't Sell Back Your Textbooks!

Outline

- Introduction
- SAG foam field trial at Cusiana Field
- Interpretation of Long-Time Diversion Data
- Implications for Field Application of SAG Foam
- Implications for Foam Modeling and Simulation

What is Foam?

- Liquid films (lamellae) separate gas bubbles, reduce gas mobility ("viscosify" the gas)
- Surfactant stabilizes the lamellae
- Foam is not a new phase, but a two-phase flow phenomenon that drastically reduces gas mobility (e.g., by 100's to 10,000's)

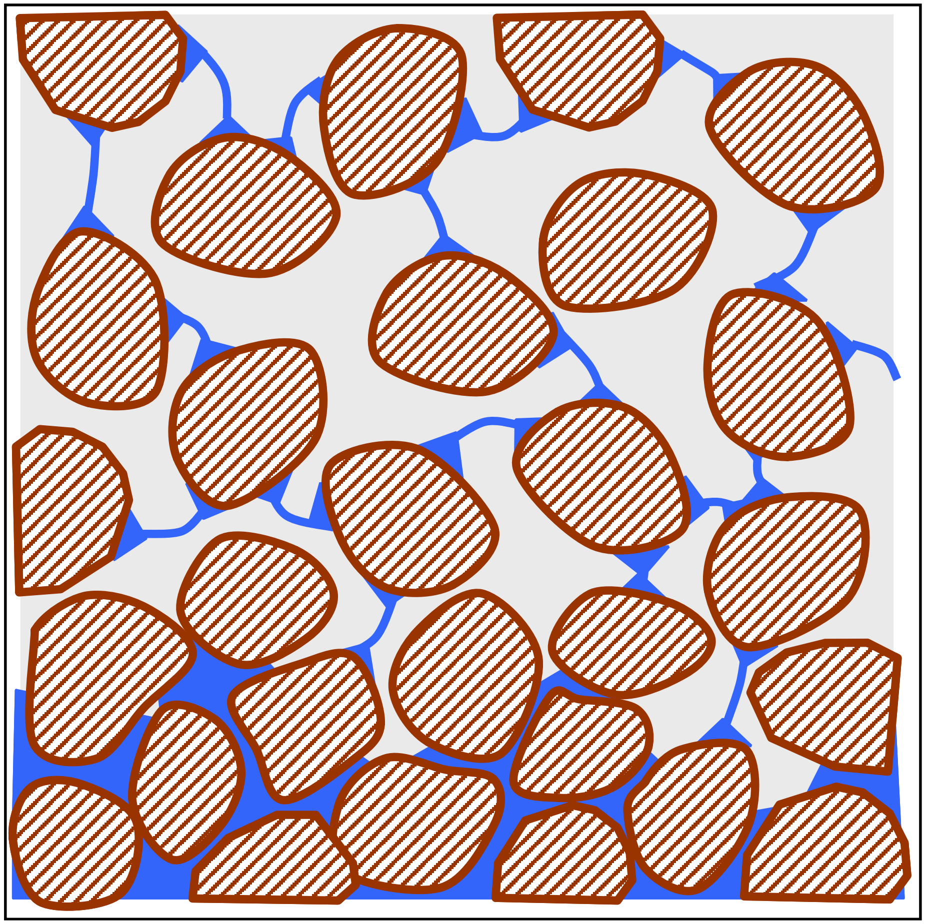


figure from S I Kam, LSU

Foam Test in Mirador Formation, Cusiana Field, Colombia

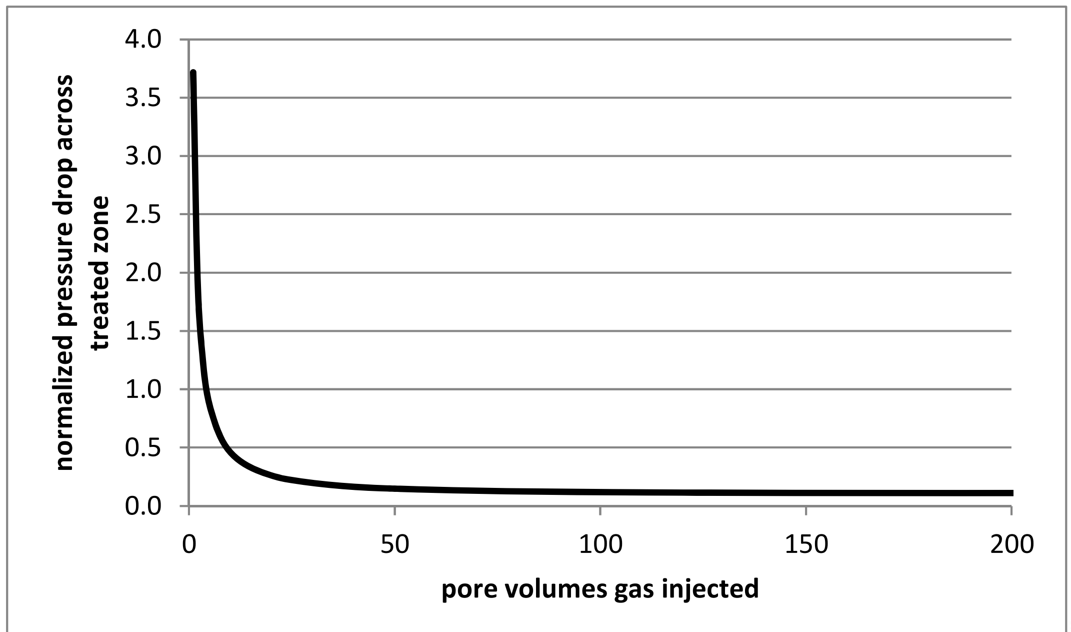
- Details of field and field test, including lab studies, in Ocampo et al., IPTC 26984 (2013)
- Cusiana Field located in Eastern Colombia; contains ~ 1.5 BBbbl oil, 3 Tscf gas; about 60% in Mirador formation
- Flow in Mirador formation is matrix-dominated
- After decade of gas re-injection, high levels of gas recycling seen in most producers
- One layer (MIR VI) takes almost half of injected gas

Foam Test in Mirador Formation, Cusiana Field, Colombia

- Design single-cycle SAG process test in one well to redistribute injection among layers:
  - Inject one slug of surfactant into layer MIR V1 *only*
  - resume gas injection into all layers: 100 MMscf/d for 2 days, thereafter 35 MMscf/d
- Two to three months later, see increased oil rate & decreased in GOR in nearby producing wells
- Details of field test in Ocampo et al., IPTC 26984 (2013)

Gas Injection in SAG Process

- In MIR VI, one slug of surfactant is followed by large slug of gas: "single-cycle SAG process"
- In radial flow, injectivity in single-slug SAG reaches minimum shortly after gas injection begins, rises thereafter as foam near well dries out and weak-ens
- See SPE 75180, 164891, 165282, 166244, 169059



Foam Test in Mirador Formation, Cusiana Field, Colombia

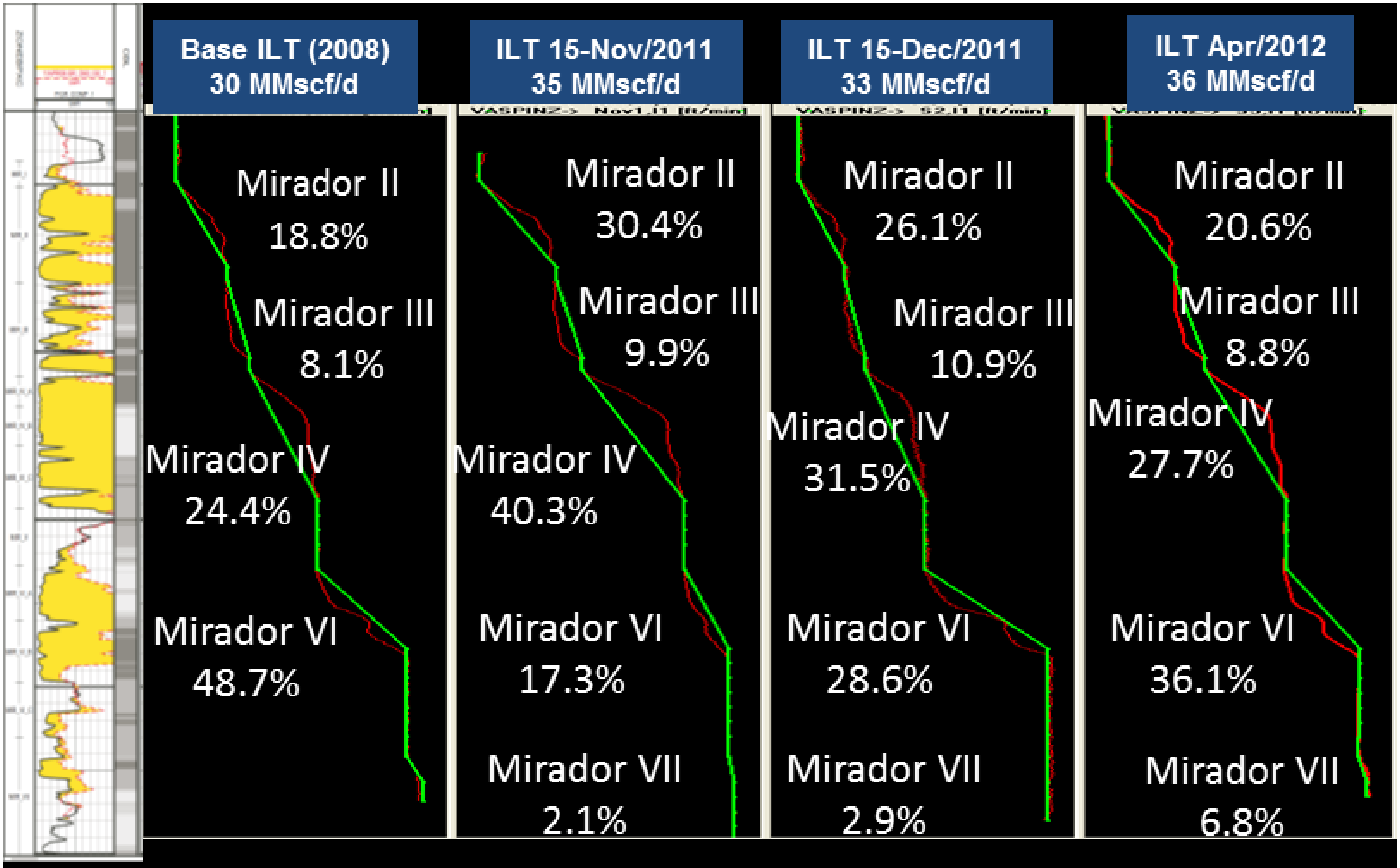
- Tricky to interpret bottomhole pressures because injection rates and density of fluids varied during foam test
- Ran injection log before test, 5 days after gas injection resumed, and twice thereafter
- Here we interpret diversion at relatively long times from injection logs
    - First PV of gas entered treated region around MIR VI within first few hours of test

Long-Time Diversion in Field Trial

- Injection logs were run before test and after long periods of gas injection
- Before test, about half of gas enters one layer, MIR VI
- With foam in layer MIR VI, fraction of gas entering MIR VI decreases, fraction entering other layers increases
- Effect decreases with time of gas injection

		ILT results		
Layer	**Baseline 2008**	**15 Nov 2011**	**15 Dec 2011**	**10 April 2012**
Mir II	18.8%	30.4%	26.1%	20.6%
Mir III	8.1%	9.9%	10.9%	8.8%
Mir IV	24.4%	40.3%	31.5%	27.7%
Mir VI	48.7%	17.3%	28.6%	36.1%
Mir VII	0.0%	2.1%	2.9%	6.8%

Injection Log Results



Radius of Treated Region

- Foam exists only as far as surfactant bank
- Material balance on surfactant: injected surfactant = surfactant in aqueous phase in pore space and surfactant adsorbed in rock
- Injected volume surfactant slug of 5400 bbl, surfactant concentration 0.2 wt%
- MIR VI thickness 21 m; porosity 0.0798
- In absence of direct data, estimate water saturation in foam bank ~ 0.4
- Adsorption measured in field cores ~ 0.35 mg/g
- Estimated radius of treated region: 5.3 m

Pore Volumes of Gas Injected into MIR VI During Test

- Pore volume defined by radius of treated region
- Gas injection rate ~ 100 MMscf/d (2.83 MMscm/d) for first two days, followed ~ 35 MMscf/d (0.99 MMscm/d) thereafter
- Formation Volume Factor B_g ~ 0.0041
- Don't know fraction of gas entering MIR VI during test before first ILT; thereafter fraction is bounded by ILT results
- Estimate 24-41 PV before 15 Nov. ILT, ~220 PV before 15 Dec.; ~1250 PV before 10 April ILT

Estimated PV Gas Injected into Treated Region of MIR VI

		ILT results		
Layer	**Baseline 2008**	**15 Nov 2011**	**15 Dec 2011**	**10 April 2012**
Mir II	18.8%	30.4%	26.1%	20.6%
Mir III	8.1%	9.9%	10.9%	8.8%
Mir IV	24.4%	40.3%	31.5%	27.7%
Mir VI	48.7%	17.3%	28.6%	36.1%
Mir VII	0.0%	2.1%	2.9%	6.8%
PV gas into layer Mir VI		~24-41	~220	~1250

Reduction in Injectivity into MIR VI

- Assume fixed reduction of injectivity into MIR VI by factor X at time of injection log test
- Assume injectivity in other layers remains unchanged from baseline value
- **Exception**: MIV VII took no gas before; it opens during test and takes increasing amount of gas with time
- Exclude this layer from cal-culations

		ILT results		
Layer	**Baseline 2008**	**15 Nov 2011**	**15 Dec 2011**	**0 April 201**
Mir II	18.8%	30.4%	26.1%	20.6%
Mir III	8.1%	9.9%	10.9%	8.8%
Mir IV	24.4%	40.3%	31.5%	27.7%
Mir VI	48.7%	17.3%	28.6%	36.1%
Mir VII	0.0%	2.1%	2.9%	6.8%

Reduction in Injectivity into MIR VI

- Assume fixed reduction of injectivity into MIR VI by factor X at time of injection log test
- Assume injectivity in other layers remains unchanged from baseline value
- Injected fraction into other layers reflects larger fraction of total injectivity with injectivity into MIR VI reduced
- Exclude MIR VII from calculations

$$F_j = \left(\frac{I_j}{XI_6 + I_0} \right) (1 - F_7), \quad j = 2, 3, 4 \qquad F_6 = \left(\frac{XI_6}{XI_6 + I_0} \right) (1 - F_7)$$

Results

		ILT results			model fit		
Layer	**Baseline 2008**	**15 Nov 2011**	**15 Dec 2011**	**10 April 2012**	**15 Nov 2011**	**15 Dec 2011**	**10 April 2012**
Mir II	18.8%	30.4%	26.1%	20.6%	30.1%	24.9%	20.5%
Mir III	8.1%	9.9%	10.9%	8.8%	13.0%	10.7%	8.8%
Mir IV	24.4%	40.3%	31.5%	27.7%	39.1%	32.4%	26.6%
Mir VI	48.7%	17.3%	28.6%	36.1%	17.8%	29.1%	37.2%
Mir VII	0.0%	2.1%	2.9%	6.8%			
injectivity factor (X), Mir VI		0.23	0.45	0.70			

- Consistent, accurate fit for layers 2, 3, 4, 6

Mobility Reduction in Treated Region of MIR VI

- Define average mobility reduction factor for treated region, Z
  - Average is highly nonlinear, heavily influenced by near-well region
- Nearest well 2900 ft away; assume r_e = 2000 ft
- Calculation similar to that for near-well damage in production engineering

$$X = injectivity\ reduction = \frac{\left(\frac{1}{Z}\ln\frac{r_t}{r_w} + \ln\frac{r_e}{r_t}\right)^{-1}}{\left(\ln\frac{r_e}{r_w}\right)^{-1}}$$

Estimated Mobility Reduction MIR VI

		ILT results		
Layer	**Baseline 2008**	**15 Nov 2011**	**15 Dec 2011**	**10 April 2012**
Mir II	18.8%	30.4%	26.1%	20.6%
Mir III	8.1%	9.9%	10.9%	8.8%
Mir IV	24.4%	40.3%	31.5%	27.7%
Mir VI	48.7%	17.3%	28.6%	36.1%
Mir VII	0.0%	2.1%	2.9%	6.8%
PV gas into layer Mir VI		~24-41	~220	~1250
injectivity factor (X), Mir VI		0.23	0.45	0.70
mobility factor (Z), Mir VI		0.12	0.27	0.51

Implications

- Foam reduced gas mobility in treated zone by factor of 8 after ~ 32 PV, 4 after 220 PV, and 2 after 1250 PV gas injection
- Early-time behavior not determined by this approach
- Foam can have modest diverting effect for many, many pore volumes
- Results also important for injectivity with larger surfactant slugs:
    - Near-well region, crucial to injectivity, sees many, many pore volumes of gas injection

Comparison to Foam Models

- In test, foam reduced gas mobility in treated zone by factor of 8 after ~ 32 PV, 4 after 220 PV, and 2 after 1250 PV gas injection
- In STARS foam model, foam never completely collapses at any water saturation
- Individual model fits to shorter-term coreflood data give different degrees of "dryout," i.e. rise in gas mobility over time of gas injection

Comparison to Foam Models

- In test, foam reduced gas mobility in treated zone by factor of 8 after ~ 32 PV, 4 after 220 PV, and 2 after 1250 PV gas injection
- Rossen & Boeije (2013) fit to data of Persoff (1991):
  - gas mobility reduced by 25x after 200 PV, 20x after indefinite injection
- Ma et al. (2013) fit to their coreflood data:
  - gas mobility reduced by 1000x after 200 PV, same after indefinite injection
- Rossen and Boeije fit to Ma et al. data with modified STARS foam model (with complete collapse at S_{wr}):
  - gas mobility reduced by 2x after 200 PV, ~ 1x after 1250 PV gas injection

Modified Version of "Dryout" in Foam Model from STARS

- STARS represents foam weakening and collapse as foam dries out with "dryout function":

$$mobility\ reduction \sim F_w = 0.5 + \frac{\arctan(epdry(S_w - fmdry))}{\pi}$$

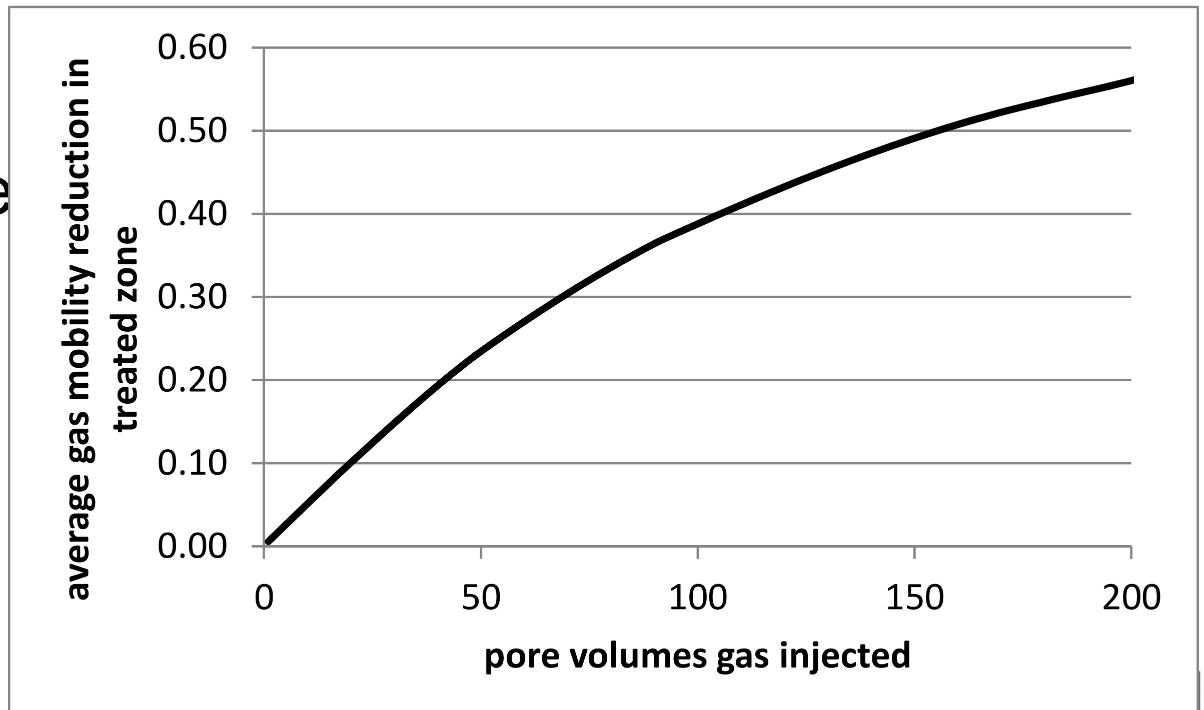
  - Function never gives complete foam collapse
  - *fmdry* reflects limiting capillary pressure (S_w*)
- Namdar Zanganeh et al. (2011) suggest modification:

$$mobility\ reduction \sim \left[F_w(S_w) - F_w(S_{wr})\right]$$

  - Foam collapses completely at S_{wr}

Model Fit with Modified STARS Model

- Modified model allows for foam collapse at S_{wr}, unlike STARS; fits coreflood data of Ma et al. (2013)
- Mobility rises a little faster than in this field test
- Data fit to different foam, rock than field tests
- Need to consider implications of dryout function in foam model and data fit for long-time behavior and injectivity



Conclusions

- The foam-treated zone was ~ 5.3 m in radius.
- Gas mobility in that zone was reduced by about 8x, 4x and 2x from its value without foam after injection of ~32, 220 and 1250 PV gas.
- Thus foam reduced mobility by a modest amount over extremely long periods of gas injection.
- Results reflect mobility very near well with larger surfactant slugs and suggest good injectivity of foam in SAG foam field applications
- A modified version of STARS model gives qualitative fit to long-time rise in gas mobility

Acknowledgements

We thank Equión Energía for permission to use the field data and to publish this paper.


Questions?