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STEAM FOAM STUDIES IN THE PRESENCE OF RESIDUAL OIL

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Abstract

The lack of understanding regarding foam flow in porous media necessitates further research. This paper reports on going work at Stanford University aimed at increasing our understanding in the particular area of steam foams.

The behavior of steam foam is investigated with a one dimensional (6'x2.15") sandpack under residual oil conditions of approximately 12 percent. The strength of the in-situ generated foam, indicated by pressure drops, is significantly affected by injection procedure, slug size, and steam quality. The surfactant concentration effect is minor in the range studied.

In the presence of residual oil the simultaneous injection of steam and surfactant fails to generate foam in the model, even though the same procedure generates a strong foam in the absence of oil. Nevertheless when surfactant is injected as a slug ahead of the steam using a surfactant alternating gas (SAG) procedure, foam is generated. The suggested reason for the success of SAG is the increased phase mixing that results from steam continually having to reestablish a path through a slug of surfactant solution.

The minimum slug size required to generate foam by SAG is about 5 percent of the model's pore volume. Above this minimum, increases in slug size or changes in surfactant concentration have little effect in the range studied. The injected steam quality, however, does affect foam strength. Reproducible results show that foam strength improves as the injected steam quality increases.

Experimental results imply that a savings in the total mass of surfactant needed for a foam flood may be possible by a SAG procedure that utilizes a sufficiently large slug volume. That is, if the slug volume is above some minimum then a dilute concentration of surfactant may give acceptable foam generation. The converse is not true however as a high concentration of surfactant in a small slug volume is ineffective. The results also indicate that the continual washing away and dilution of surfactant by low quality steam injection is detrimental.

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1. Introduction

Successful field and lab studies confirm that steamflood efficiency improves when surface active agent (surfactant) is injected in sufficient quantity to enable the generation of foam within a porous medium. Such foams greatly reduce steam mobility in areas of low residual oil saturation and effectively counter the tendency of steam to channel and override. The resulting diversion of steam to previously unswept areas translates into better sweep efficiency and increased oil production.

While the benefits of foam have been frequently verified, the most cost effective applications probably have not been attained since such optimum applications require thorough understanding of the physics involved. Unfortunately, the lack of thorough understanding is apparent upon a review of the existing literature. Such a review shows contradictions concerning the relationship of foam resistance with bubble texture, quality, gas velocity, fluid velocity, injection method, and formation permeability. These contradictions remain since the reasons why they can exist are not fully understood. This implies that the cost effective application of the technology relies more on trial and error than exact science. A logical conclusion is that more research is needed, although such research often generates more questions than answers.

A particular phenomenon found here at Stanford is that the simultaneous injection of steam and surfactant into a linear sandpack causes strong foam generation in the absence of oil but no generation in its presence. Although a reduced response is expected in the presence of oil, the lack of a pressure increase, together with the lack of an explanation, adds yet another dilemma regarding foam flow in porous media. This research aims at providing an explanation and a solution to the dilemma, then to optimize the solution. The solution is provided by M.R.B. Demiral (previously unpublished RUNS 1, 2, and 3 of this report), the partial optimization requires an additional four runs, and the suggested explanation is based upon the results of these seven runs and the results of previous researchers. Also included in this investigation is an attempt to explain some of the contradictions mentioned in the previous paragraph through the introduction, development, and application of the transport mode concept.

2. Literature Survey

2.1 Introduction to Literature Survey

The literature review indicates that our knowledge regarding foam flow is incomplete, which is understandable considering the difficulty in seeing what occurs in-situ. Micromodels have greatly helped and a recent improvement in micromodel construction (Hornbrook et al [1991]) shows much promise.

However, until further foam experiments using the new micromodel are performed, a fuller understanding of foam flow requires continuing use of the indirect methods of pressure and temperature monitoring such as used in this lab study. An additional approach is to reanalyze existing data. This literature survey is an example of the reanalysis approach and aims at reconciling the contradictions regarding the effects of foam quality and formation permeability. Also included is a discussion on oil and injection technique effects since these factors strongly influence the results of the laboratory study undertaken.

To facilitate reading of the discussions concerning the above mentioned effects, some basic introduction concerning texture and wettability is included. Also included is a short description of the transport mode concept, which is developed and applied during the reviews to follow.

2.2 Transport Mode Concept: MAB vs BTT

The transport mode concept (TMC) refers to the idea of foam flow modes. A review of the literature shows that two types of flow are variously described. Here they are called (1) the 'unstable' making and breaking (MAB) mode,

> Holm (1968), Mast (1972), Owete and Brigham (1984), Ettinger and Radke (1989), Yang and Reed (1989),

and (2) the 'stable' bubble train translation (BTT) mode,

> Hirasaki and Lawson (1985), Falls et.al. (1989), Huh et.al. (1989), Yang and Reed (1989).

MAB refers to the case where translational flow of bubbles through pore throats is negligible and foam is constantly forming and rebreaking. BTT refers to the case where bubble trains can travel through the pore throats without rupturing. The former is an unstable foam and the latter a stable foam. The result is that BTT foams are stronger and have a greater resistance to gas flow than MAB foams.

Predicting the conditions favoring a weak or strong foam is needed since some applications can preferentially benefit from having one or the other. Such predictions of MAB vs BTT require a consideration of the factors affecting foam stability in porous media. The next section lists the many factors affecting foam stability, however only three primary factors are used for mode prediction: (1) the porous medium permeability; (2) the surfactant concentration, and; (3) the injected foam quality, or, in some cases, the porous medium in-situ gas saturation. These three factors along with surfactant type are usually the principal variables in carefully controlled laboratory experiments. Their interplay significantly affects foam stability and transport mode.

Foam stability involves a balance between the capillary forces tending to cause coalescence and the electrostatic repulsions tending to retard coalescence (Chambers and Radke [1990]). Low

Table 2.1: Rough Guide to Predicting Transport Mode

Concentration wt%	Permeability Darcy	Quality/Gas Saturation %	Expected Mode MAB vs BTT
0.1	5	85/60	?
1.0	5	85/60	BTT
0.01	5	85/60	MAB
0.1	30	85/60	BTT
0.1	0.5	85/60	MAB
0.1	5	75/40	BTT
0.1	5	95/80	MAB

surfactant concentrations are detrimental since they result in weak electrostatic repulsions. Similarly, low permeabilities and low water saturations (or high injected foam qualities) are detrimental since the resulting capillary pressures imposed upon the lamellae are high. The problem is in deciding what permeability, surfactant concentration, and foam quality (or gas saturation) is high or low. The results from the literature survey provide some help as, in general, a transition zone between MAB vs BTT appears to exist at 5 darcies permeability, 0.1 wt% surfactant concentration, and 85% foam quality. These values are very rough since the surfactant type is important in regard to transport mode (Yang and Reed [1989]), nevertheless they do provide a reference point from which predictions of flow type can be made. For example, experimental conditions having 5 darcies permeability, 0.1 wt% surfactant concentration, and 95% foam quality would be expected to have foam flow by the MAB mode. Conversely, under the same conditions but with 75% foam quality the expected mode would be BTT. Significantly raising permeability or concentration, or lowering quality from the above suggested transition zone values favors BTT. Conversely, significantly lowering permeability or concentration, or raising quality from the above suggested transition zone values favors MAB. As a further aid: a permeability above 30 darcies is considered high, while a permeability below 500 md is considered low; a concentration above 1.0 wt% is considered high, while a concentration below 0.01 wt% is considered low, and; a quality below 75% is considered low, while a quality above 95% is considered high. Benchmark values for in-situ gas saturation are more difficult to provide since these values are less often reported, but, from the research reviewed, a gas saturation below 40% is considered low and a gas saturation above 80% is considered high. From the above discussion then, a system having 30 darcies permeability, 1.0 wt% surfactant concentration, and 85% injected foam quality would strongly favor the BTT mode , while a system having 0.5 darcy permeability, 0.01 wt% surfactant concentration, and 95% injected foam quality would strongly favor the MAB mode. Table 2.1 below should help in further clarifying the discussion.

Assuming that transport mode can be predicted, how can this aid in resolving conflicting results or of predicting for example whether gas resistance actually increases or decreases with quality? This question will be addressed later in the report after first providing some background information on bubble texture and rock wettability.

2.3 Bubble Texture and Foam Stability

Bubble-texture is affected by several factors, especially the porous medium

Sharma (1965), Kovalchuk (1968), Ettinger and Radke (1989), Owete and Brigham (1984), Hornbrook et al (1991), de Vries and Wit (1990), the surfactant type

Sharma (1965), Raza (1970); Mast (1972); Holbrook et al (1981); Sharma et al (1986), Marsden et al (1967),

and the surfactant concentration

Sharma (1965), Mast (1972), Owete and Brigham (1984), Treinen et al (1985), Marsden et al (1967).

Additionally, texture's dependence on gas velocity (or pressure gradient) is implied by the experimental result that gas apparent viscosity depends upon gas (shear) rate

Marsden and Khan (1966), David and Marsden (1969), Holcolmb et al (1981), Holbrook et al (1981), Hirasaki and Lawson (1985), Treinen et al (1985), Yang and Reed (1989), Lee and Heller (1990).

The overall combination of these factors — porous medium, surfactant type, surfactant concentration, and gas velocity — determine bubble texture and foam stability in-situ. The contributions from these factors are discussed further below.

2.3.1 Porous Medium

The influence of the porous media includes effects of bubble generation and termination

Ransohoff and Radke (1988), Chambers and Radke (1990);

wettability

Suffridge et al (1989), Sanchez and Hazlett (1989), Morrow (1990), Hirasaki (1991), Huh et al (1989);

capillary pressure

Jimenez and Radke (1988), Khatib et al (1988), Chambers and Radke (1990);

hydrocarbon saturation

Bernard and Holm (1964), Al-Khafaji et al (1982), Jensen and Friedmann (1987), Bernard et al (1964), Lau and O'Brien (1988) Hudgins and Chung (1990);

brine concentration

Dilgren (1982), Al-Khafaji et al (1982), Duerksen (1986);

temperature

Al-Khafaji et al (1982), Robin (1985);

adsorption

Al-Khafaji and Castanier (1984);

and pH

Robin (1985), Buckley et al (1989), Morrow (1990).

Generally, a finer textured and more stable foam is favored by: low brine level (decreased surfactant precipitation); low adsorption and hydrocarbon saturation (reduced surfactant losses); low capillary pressure and high water wettability (decreased coalescence); high pH (lessened oil wettability), and; low temperature (reduced surfactant degradation).

2.3.2 Surfactant Type and Concentration

The surfactant type and concentration influence, in conjuction with capillary suction, whether foam flows predominatly by the 'unstable' making and breaking (MAB) mode

Holm (1968), Mast (1972), Owete and Brigham (1984), Ettinger and Radke (1989), Yang and Reed (1989)

or by the 'stable' bubble train translation (BTT) mode

Hirasaki and Lawson (1985), Falls et al (1989), Huh et al (1989), Yang and Reed (1989).

Generally, for anionic surfactants, higher surfactant concentration and hydrophobicity favor the latter, more resistive mode of foam flow

Shallcross et al (1990), Robin (1985) Yang and Reed (1989).

2.3.3 Gas Velocity (pressure gradient)

Gas velocity influences bubble generation

Ranshohoff and Radke (1988), Chambers and Radke (1990),

bubble termination

Jimenez and Radke (1988), Chambers and Radke (1990),

and, by implication, foam transport mode (BTT vs MAB). Both shear thinning

Marsden and Khan (1966), David and Marsden (1969), Holcomb et al (1981), Holbrook et al (1981), Hirasaki and Lawson (1985), Treinen et al (1985), Yang and Reed (1989), Lee and Heller (1990), Suffridge et al (1989)

and shear thickening

Yang and Reed (1989), Suffridge et al (1989)

trends are possible experimentally, with the gas velocity's relative affect on bubble generation/termination and transport mode (MAB/BBT) being the determining factors.

2.4 Wettability Effects

To gain a better understanding of the factors affecting wettability, researchers such as Hirasaki (1991), Buckley et al (1989), and Morrow (1990) use an intermolecular surface force model. Such an approach, based upon the Derjaguin, Landau, Verwey, and Overbeek (DLVO) theory of colloid stability (see Hirasaki), expresses surface forces as disjoining pressure isotherms. Jiminez and Radke (1988) use a similar approach to discuss foam stability. These isotherms are a sum of van der Waals attractions, electrostatic repulsions, and short range structural (solvation) repulsions. Buckley et al use a DLVO based model to successfully predict adhesion behavior of crude oils on glass surfaces. They show adhesion to be dependent upon pH and sodium ion concentration, with high pH (low H+ conc.) and low Na+ concentration favoring nonadhesion. Morrows states that the outcome of adhesion tests and the maintenance of water wetness in a reservoir depends on the stability of thin water films, with unstable water films giving crude oil access to solid surfaces. Such access allows polar components to adsorb and alter rock properties, resulting in a condition of mixed wettability. Since polar components in oil affect wettability this would imply that oil composition is important. Morrow (Referencing Dubey and Waxman [1989]) remarks that the adsorption of high molecular weight colloidal particles (asphaltenes) suspended in crude oil is considered responsible for oil related wettability alterations. Referencing a separate work (Buckley and Morrow [1990]), Morrow states that alphaltenes' role in wettability alteration has been further confirmed by the observation that deasphalted crude oil no longer exhibited adhesion in the low pH range. Whether or not a rock is oil or water wet depends on the matrix type as well as the oil type. Therefore, the types and distribution of minerals at the surface of pore walls are important. This is understandable considering the familiar result that calcite and quartz have different wetting properties, with calcite usually being more oil wet than quartz. That calcite is more oil wet is consistent with the knowledge that it has a more positive surface charge than quartz. It is also consistent with the results of Buckley et al, where high H+ and Na+ favor oil adhesion. Such cations reduce the maximum disjoining pressure and result in less stable water films.

In summary, the oil type, rock type, pH, and salinity can play important roles in determining wettability. This knowledge has led to a growing realization that the common assumption of a reservoir sand being very strongly water wet is probably a poor assumption to make. This, in turn, has led to a further consideration of wettability in regard to foam flow, since foam stability requires at least partially water wetting rock surfaces.

The above discussion on wettability completes the introductory background information. The following sections, beginning with permeability effects, rely upon the material covered to this point.

2.5 Permeability Effects

The preponderance of core, pack, and capillary tube experimental data indicate that higher permeability (or larger capillary size) is conducive to foam strength

Bernard and Holm (1964); David and Marsden (1966); Hirasaki and Lawson [1985]; Yang and Reed (1989); Lee et al (1990); Llave et al (1990); Lee and Heller (1990).

Not all researchers, however, find the same effect.

Khatib et al (1988); Yang and Reed (1989).

The result is that there exist two apparently contradictory permeability effects, with foam strength seeming to both increase and decrease with permeability. Since texture is of paramount importance when considering foam strength

Hirasaki and Lawson (1985), Persoff et al (1989),

it is reasonable to expect that variations in texture with permeability and experimental procedure are at the root of this apparent contradiction. As will be shown, however, texture alone does not give a satisfactory answer in porous medium. A plausible explanation requires use of the previously discussed transport mode concept.

Bubble texture is strongly shaped by the porous media

Kovalchuk (1968), Ettinger and Radke (1989), de Vries and Wit (1990),

with bubble size being on the order of the pore body size

Owete and Brigham (1984), Hornbrook et al (1991).

Depending upon surfactant type and concentration, the bubble size stabilized in porous media may be a factor of 2 or 3 greater or lesser than the pore body size. The stronger, more concentrated, surfactant solutions retard coalescence forces sufficiently to stabilize the smaller bubbles generated by subdivision mechanisms, while the weaker, more dilute, surfactant solutions are more susceptable to capillary suction coalescence, resulting in an average bubble size possibly larger than the pore size. This implies that bubble size should decrease as permeability (pore size) decreases, and, since foam of finer texture has more lamellae per unit length and a greater resistance to flow (Hirasaki and Lawson [1985]), that apparent viscosity should increase as permeability decreases. Such a scenario is predicted by the combined capillary radius and bubble size effect of Hirasaki and Lawson (1985), Figure 2.1. However, this contradicts the majority of experimental data.

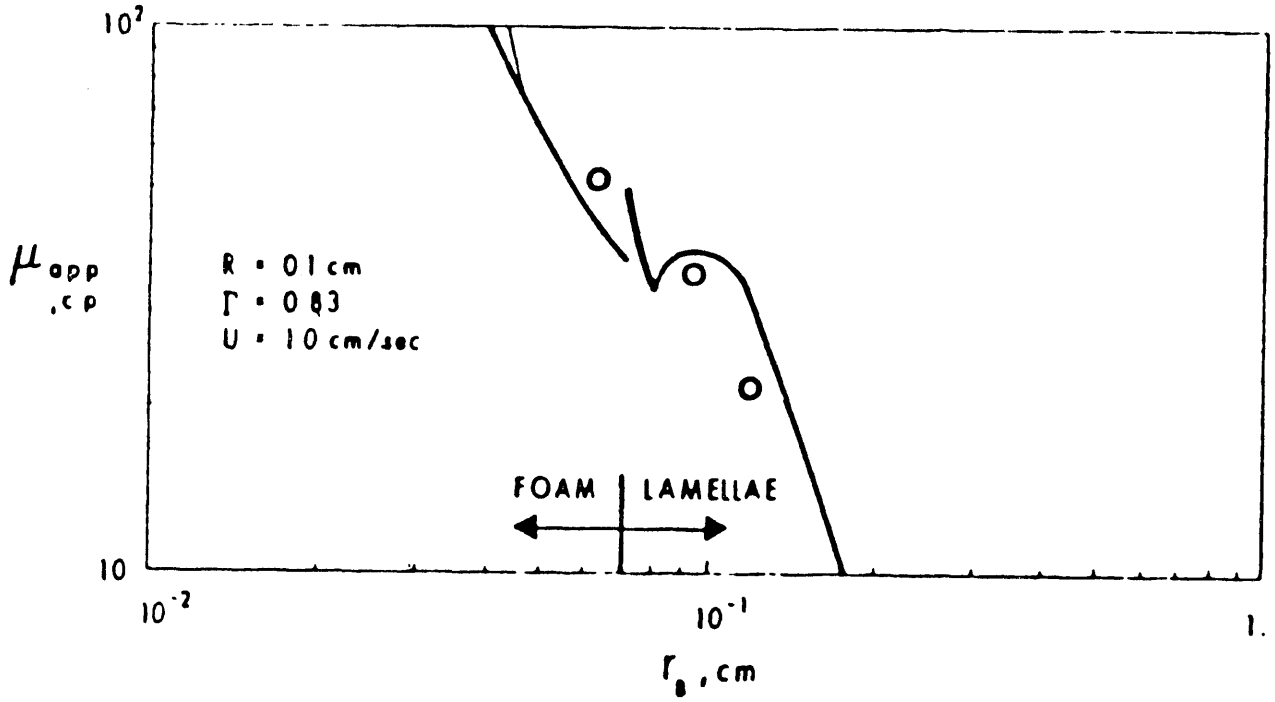


Figure 2.1: Hirasaki and Lawson (1985), For a fixed bubble/capillary radius, Gas Resistance Decreases with Pore Body Size

What is lacking in the above argument is a discussion of the factors that stabilize (surfactant type and concentration) or destabilize (high capillary suction) in-situ foam. The influence that these stabilizing and destabilizing factors have on foam strength (Jimenez and Radke [1988], Chambers and Radke [1990]) and foam transport mode is extremely important. Of special interest is how the combination of texture, stability, and transport mode can explain 'contradictory' results.

Yang and Reed, finding both the above mentioned permeability effects, use the transport mode concept to discuss their results. They conclude that the different transport mechanism between stable and unstable foam is the explanation for the contradicting dependence of resistance on permeability. Their reasoning is put forth and extended in the following discussion. Basically, with stable foam the translational flow of lamellae through pore restrictions (bubble train transport [BTT]) generates large pressure gradients. Assuming that BTT stays predominant and assuming that the smaller pores shape the foam into smaller bubbles as discussed previously, then as permeability (pore body size) decreases the pressure gradient will increase. This increase in pressure gradient is a result of an increase in the number of lamella per unit length being transported and, perhaps more importantly, a result of the increased displacement pressure needed to overcome increased capillary pressure and lamella curvature. This scenario is in agreement with the argument presented in the previous paragraph and in agreement with the minority of laboratory data. For this type of foam flow (BTT), coalescence plays a minor role as the time to coalesce is long. However, for unstable foam (make and break [MAB]) the coalescence time, playing a major role, is too short to allow for translational flow of lamellae through pore restrictions. Instead, the stationary lamella act as barries to flow. For these unstable foams, increasing permeability causes coalescence time to increase, and, therefore, the amount of lamellae barriers to increase. The resulting increase in resistance with permeability is in agreement with the majority of laboratory data. So, both types of permeability dependence are understandable considering tranport mode changes.

The transport mode (BTT vs MAB) concept implies that at sufficiently low permeabilities any given surfactant foam should transport by MAB and have a 'favorable' permeability dependence. Favorable, that is, in the sence that high permeability streaks are preferentially plugged. The same surfactant foam at sufficiently high permeabilities should transport by BTT and have an 'unfavorable' permeability dependence. Actually, the theoretical work of Khatib et al (1988) — relating gas mobility to absolute permeability and based upon limiting capillary pressure arguments — predicts such a changing permeability dependence. Additional visual experiments aimed at proving the theory of Khatib et al and at verifying changes in transport mode with permeability would be helpful. If such experments corroborate the above discussion, then future attention at mobility reduction in porous media would need to focus on both texture and transport mode.

In lieu of visual experiments, a minimal check for the validity of the transport mode concept can be made by reviewing the above referenced researchers. If they find foam strength is proportional to permeability then their experimental conditions must indicate that MAB is the expected mode of transport in the lowest permeability medium used. In such cases increasing permeability reduces capillary driven coalescence and increases foam stability. Or, if their results show foam strength is inversely proportional to permeability then the their experimental conditions must indicate that BTT is expected in the lowest permeability medium used. In such cases the coalescence time is long even in the low permeability medium so reducing capillary pressure by increasing permeability does not significantly impact stability. Rather, the larger bubbles expected in higher permeability medium have less resistance to flow. Such a review follows below.

Bernard and Holm (1964) used Berea cores (100 to 250 md; 6 to 30 inches long; 20% porosity) and sandpacks (3 to 150 D; 1 to 30 ft long; 40% porosity) with a steady state procedure where surfactant (type not disclosed) and nitrogen gas were injected continuously. To check foam strength vs absolute permeability, a 225 md Berea core, and sandpacks of 3.35 and 146 D were used. They then plotted gas permeability vs in-situ gas saturation for each medium. Their results, Figure 2.2, show that at any given gas saturation above 40%, gas resistance increases with absolute permeability. For example, at 50% in-situ gas saturation the gas permeability of the 225 md core was 1.5 md, the 4 D sandpack had 0.3 md of gas permeability, and the 146 D sandpack was still below its critical gas saturation and impermeable to gas. These results require only that the mode of transport for the 225 md core and the 3.35 D sandpack be by MAB above 40% gas saturation. This is reasonable since lower permeabilities at the same gas saturation are more destabilizing as they exert higher capillary suction pressures. Unfortunately, a more complete argument is not possible since the surfactant type and concentration are not available. Nevertheless , unless the concentration is very high, BTT is not expected in the 225 md core except at low gas saturations. Conversely, unless the concentration is quite low, MAB is not expected in the 146 D sandpack except at very high gas saturations. Only the 3.35 D sand is in question since its intermediate

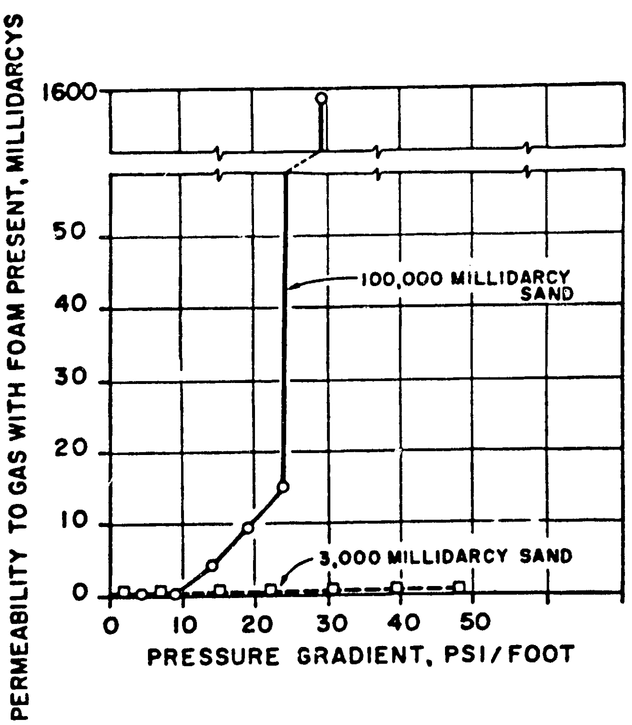


Figure 2.2: Bernard and Holm (1964), Gas Resistance Increases with Absolute Permeability

value of permeability puts it on the borderline (at these gas saturations) between where BTT stops and MAB begins, as discussed previously.

Lee et al (1990) generated foam in-situ by simultaneous injection of CO2 (flowing fraction 80%) and surfactant solution (0.1 wt% of Enordet X2001(A)) into short (2.54 cm) sandstone, limestone, and dolomite cores having permeabilities ranging from 0.4 to 302 millidarcies. Their results, Figure 2.3, show that resistance increases with permeability. This requires foam flow by the MAB mode (to insure consistency with the concept). This is a reasonable requirement considering the low permeabilities and moderate concentration used, however, mixing different rock types does add another factor.

Llave et al (1990) generated foam in-situ by slug injection of surfactant solution (1.0 wt% Alipal CD-128, 0.1 PV) followed by continuous injection of nitrogen. The two Berea cores (12" length x 1.5" diameter) having permeabilities of 87 and 395 md were connected in parallel. Their result that resistance is proportional to permeability requires MAB flow for the 87 md core. MAB is expected considering the low permeability, although the high concentration might have made BTT possible in the 395 md core. The results agree with the transport mode concept, but, the procedure of putting cores in parallel adds an additional factor that favors preferential plugging of the higher permeability medium for reasons other than MAB vs BTT arguments. Namely, since the cores are in parallel most of the injected 0.1 PV slug enters into the medium having the higher permeability. The resulting increased surfactant availability, in addition to the lower capilary suction pressure, favors a stronger foam. Practically, their results imply that preferential plugging of high permeability streaks in real heterogeneous reservoirs would be strongly favored simply because of increased surfactant flow into such streaks.

Lee and Heller (1990) injected pregenerated CO2 foam into Rock Creek (14.8 md) and Berea sandstones (305 md) at various qualities. For the Rock Creek sandstone the surfactants used were Chembetaine BC-50 (0.10 wt%) and Alipal CD-128 (0.05 wt%), while for the Berea sandstone the surfactants used were Varion CAS (0.03 wt%) and Enordet X2001 (0.05 wt%). The result that a weaker foam formed in the 14.8 md medium requires flow by MAB, which is expected considering the

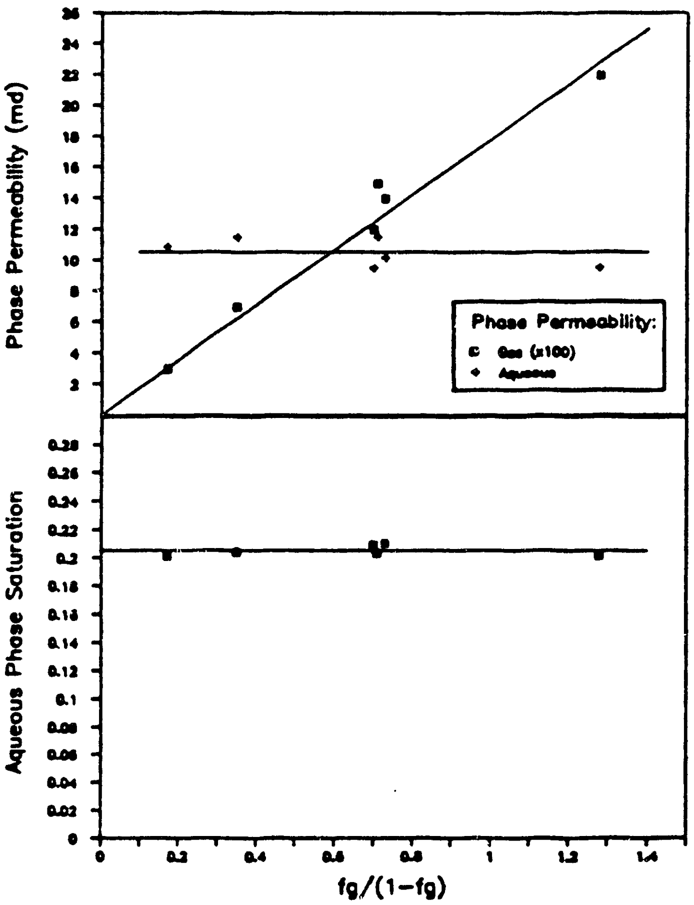


Figure 2.3: Lee et al (1990), Gas Resistance Increases with Absolute Permeability

low permeabilities and concentrations used. One problem is that different surfactants were tested. Perhaps, as pointed out by Lee and Heller, the use of different surfactants is overshadowed by the large (36 times) relative foam mobility difference observed (the ratios of absolute permeabilites is 21). This assumption may be valid, however, the results of Yand and Reed (1989) would caution against such an assumption.

Yang and Reed (1989) found both types of permeability dependance. Their results, Figure 2.4 show the importance of the surfactant type as, under similar conditions, an unstable C16-DPEDS (0.1 wt%) and a stable' NES-25 (0.1 wt%) foam had different permeability dependances. The use of C16-DPEDS, considering the moderate concentration and low permeability range of 150 to 400 md, gave the expected result of increasing resistance with permeability. However, the use of NES-25 in the range of 120 to 450 md showed the opposite result. As explained previously, Yang and Reed postulated that the NES-25 allowed for propagation of bubble trains, while the C16-DPEDS allowed only for breaking and reforming, or BTT vs MAB.

The results from the capillary tube viscometers used by David and Marsden (1966) and from the capillary tube studies in general by Hirasaki and Lawson (1985) show that foam resistance increases with increasing capillary size. This result would seem to contradict the transport mode concept since flow in capillary tubes is certainly by BTT. However for the work of Hirasaki and Lawson, for example, focusing on capillary size effects required that all other variables be held constant. The result is that injecting a fixed bubble size will mean that larger capillaries have more bubbles and lamellae per unit length and, therefore, have an increased resistance (see Figure 2.5). So it makes sense that in capillary tubes gas resistance should increase with capillary size.

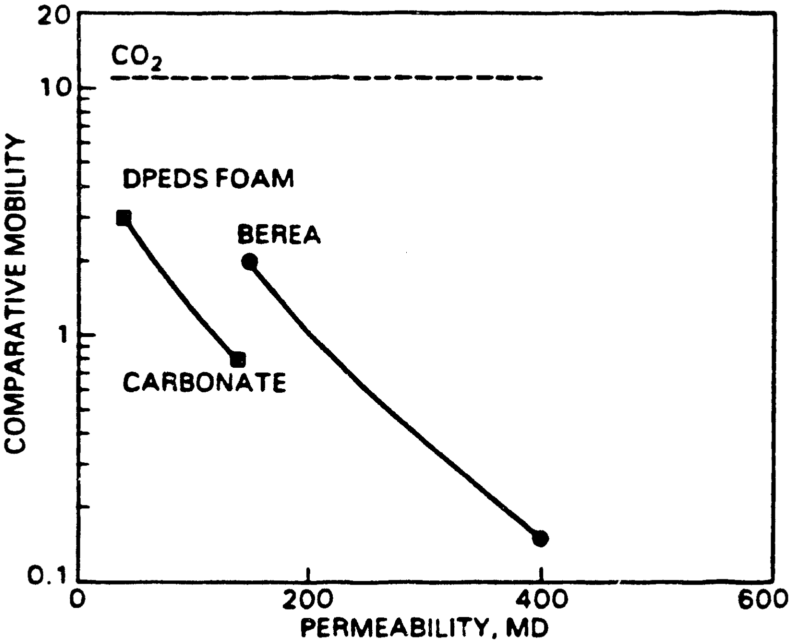


Figure 2.4: Yang and Reed (1989), Gas Resistance Can Both Increase or Decrease with Absolute Permeability, Depending upon the Surfactant

The above literature review using the transport mode concept does not give a definitive answer, but there is a strong trend that lends itself to interpretation by this concept. In the following section, the concept will be used to understand contradictions in foam strength vs foam quality results that have been reported.

2.6 Quality Effects

Experimental results confirm that foam resistance can both increase

> Marsden and Khan (1966), Kovalchuk (1968), Holbrook et al (1981), Hirasaki and Lawson (1985), Treinen et al (1985), de Vries and Wit (1990), Robin (1985)

and decrease

> Fried (1961), Holm (1968), Holbrook et al (1981), Dilgren (1982), Treinen (1985), Jensen and Friedmann (1987), Huh and Handy (1989), de Vries and Wit (1990)

as foam quality rises. To resolve this apparent contradiction the transport mode concept is used.

In reviewing the results of the directly above referenced researchers, Holbrook et al (1981), Treinen et al (1985), and de Vries and Wit (1990) observe both increasing and decreasing resistance with increases in foam quality, although only de Vries explicitly states both trends. Generally, those who find that resistance is inversely proportional to foam quality measure apparent viscosity using pressure drops across porous media. While those who find that resistance is proportional to foam

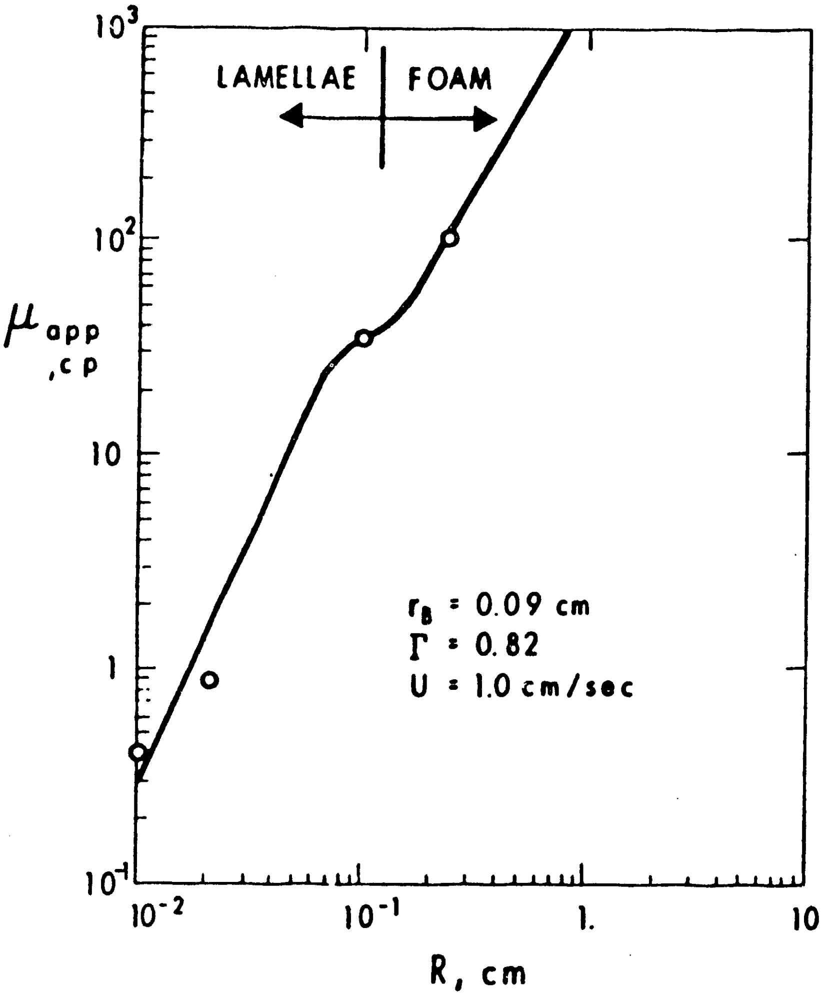


Figure 2.5: Hirasaki and Lawson (1985), Gas Resistance Increases with Capillary Radius

quality use capillary tubes or some other 'external' method to quantify apparent viscosity. Of the three researchers who find both results, Treinen et al and de Vries and Wit use porous media while Holbrook et al use capillary tubes. This observation is important because, as will be discussed later, only under special circumstances can the foam resistance as measured across porous media be proportional to foam quality. Similarly, only under special circumstances can the apparent viscosity as measured using capillary tubes be inversely proportional to foam quality. As will be shown, the above work is amenable to interpretation by the transport mode concept.

Consider first the results of Treinen (see Figure 2.6). Treinen injected pregenerated nitrogen foam of known quality into sandpacks of known properties (7 D; 37% porosity; 2 ft length). The apparent viscosity was calculated using the steady state pressure drop across the pack, and an observation cell downstream of the sandpack was used to determine texture. The results, using Suntech IV (0.005 to 0.3 wt%), vary significantly with concentration in the reported range of 70 to 90% foam quality. For the lowest concentration of 0.005 wt%, the apparent viscosity (21 cp at 70% quality) shows a small decrease with rising foam quality. For this low concentration (0.005 wt%), foam transport is expected to be by MAB, since the low concentration, even at the fairly high absolute permeability of 7 D and somewhat low quality of 70%, cannot sufficiently stabilize lamella for flow by BTT through pore throats. This speculation is strengthened by Treinen's observation that at 75% quality the foam breaks down into a free gas and a fluid with large distorted bubbles. Actually it is surprising that the apparent viscosity does not decrease more sharply with foam quality increases. Possibly the decrease is offset by the proportionality of lamellae amount with foam quality. That is, as foam quality increases with constant bubble size, more lamellae are injected, requiring more bubbles to be reshaped by the first few inches of porous medium, and,

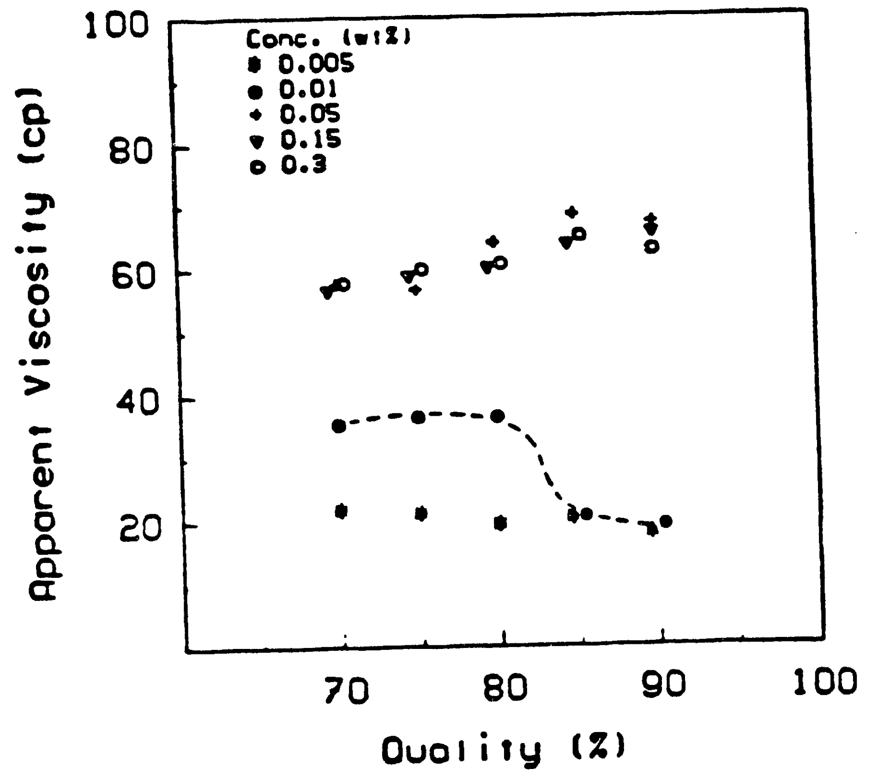


Figure 2.6: Treinen et al (1985), Gas Resistance Can Both Increase and Decrease with Foam Quality

therefore, causing more resistance. Also, the relative change in injected foam quality probably does not correspond to a similar relative change in the more important in-situ gas saturation. When Treinen increased the concentration to 0.01 wt%, the apparent viscosity at 70% quality increased from 21 to 35 centipoise. This is expected since the higher concentration (0.01 vs 0.005 wt%) further stabilizes the foam and increases the number of lamellae flow barriers. At this higher concentration the viscosity stays essentially constant when the foam quality is raised from 70 to 80 percent, reflecting increased foam stability. Nevertheless, the expected mode is still by MAB except that the number of lamellae barriers has increased, or, viewed differently, they are longer lived. This inferrence is based upon results at even higher concentrations and by the fact that at 85% quality the foam breaks down in the same manner that the 0.005 wt% solution does at 75% quality. The higher quality foam breakdown is an additional indication of the increased stability resulting from the higher concentration, showing that a higher capillary suction pressure is retarded at 0.01 wt% vs at 0.005 wt% concentration. At even higher concentrations (0.05,0.15,and 0.3 wt%) the apparent gas viscosity for all cases is 56 cp at 70% foam quality. This higher and constant viscosity above 0.05 wt% surfactant concentration is indicative of foam flow by BTT, where the coalescence time is sufficiently long to allow for lamellae translation through pore throats. The observed proportionality of resistance with foam quality is expected in BTT mode because of the increased displacement pressure needed to mobilize finer lamellae in overcoming the larger capillary pressure and lamella curvature associated with higher foam qualities. Yet, the observed proportionality of viscosity with quality is very slight, indicating that strong coalescence forces are inhibiting the expected increase. In fact at only 85% quality a break point is apparent. This break point is reminiscent of results seen by Holbrook et al (1981), de Vries and Wit (1990) and Khatib et al (1988) and may represent the onset of MAB. After the breakpoint the downward trend should have continued with further increases in foam quality had Treinen elected to increase quality more.

Holm(1968) using 2' x 1.5" unconsolidaded, and preequilibrated (0.1wt% modified ammonium lauryl sulfate ,O.K. liquid) sandpacks having an approximately permeability of 5 darcies, injected pregenerated foam at 75 and 90% quality. Upon attainment of steady state conditions, the results ($k_g \sim 1md, k_w \sim 20md$ at 75% quality; $k_g \sim 6md, k_w \sim 27md$ at 90% quality) show foam resistance being significantly inversely proportional to foam quality. This inverse proportionality requires that MAB be the primary mode of foam transport. Holm — observing that a change in gas type required about 0.63 PV of injection at each quality before detection at the effluent — concluded that "the foam bubbles broke and reformed in the sandpack". Holm's conclusions and results are in agreement with the transport mode concept in indicating flow by MAB. In this particular case, however, the moderate values of permeability, quality, and concentration, would make prediction difficult.

Kovalchuk (1968), using four short porous media consisting of either sand or glass spheres and having permeabilities of from 34 to 299 darcies, injected pregenerated air foam (1.0wt% Arquad 12-50) at qualities ranging from 0.54 to 0.94 percent. The results show foam resistance being proportional to quality, which requires transport by BTT. For these conditions BTT is expected since the high concentration (1.0 wt%) and high permeabilities favor strong foams with long lived lamellae that can translate through pore restrictions.

Robin (1985), simultaneously injected nitrogen and surfactant solution into porous medium consisting of 500 micrometer glass beads. The surfactants (1.0 wt% [names not disclosed]) included both 'conventional' hydrocarbon chain sulfonates and 'substituted' types where the usually oleophilic tail is made less so by a partial subtitution of the hydrocarbon chain. The exact permeability of the medium was not provided, but a value of over 100 D is expected as a 500 micrometer glass bead pack of Ransohoff and Radke(1988) had a permeability of about 140 darcies. Under such conditions of high permeability and surfactant concentration, the formation of very strong foams flowing by BTT would be expected. As discussed previously, this requires that resistance increase with quality, which agrees with Robin's result.

The capillary tube studies of Holbrook et al (1981), see Figure 2.7, and Hirasaki and Lawson (1985), see Figure 2.8, show (except at very high qualities for Holbrook) that foam resistance is proportional to quality, which indicates BTT. Their results are understandable as foam flow in capillary tubes under most conditions is certainly by bubble trains. That Holbrook et al show a break point at very high qualities is also expected as the increase in capillary suction and decrease in surfactant mass at high foam qualities can bring about the onset of MAB even in capillary tubes. Hirasaki and Lawson attibute the large proportionality of foam resistance with quality to the slight effect of increased lamellae and, especially, to the effect of increased bubble curvature at plateau borders at high qualities. As discussed previously, both increased lamella curvature and quantity contribute to higher BTT resistance as quality is raised, although in porous media the effect of increased lamellae quantity is expected to be quite small as the porous media shapes the foam texture to agree with pore body sizes. Nevertheless, a reasonable resistance increase from lamellae quantity may occur when foam is pregenerated since the reshaping occuring within the first few inches results in an increased pressure drop.

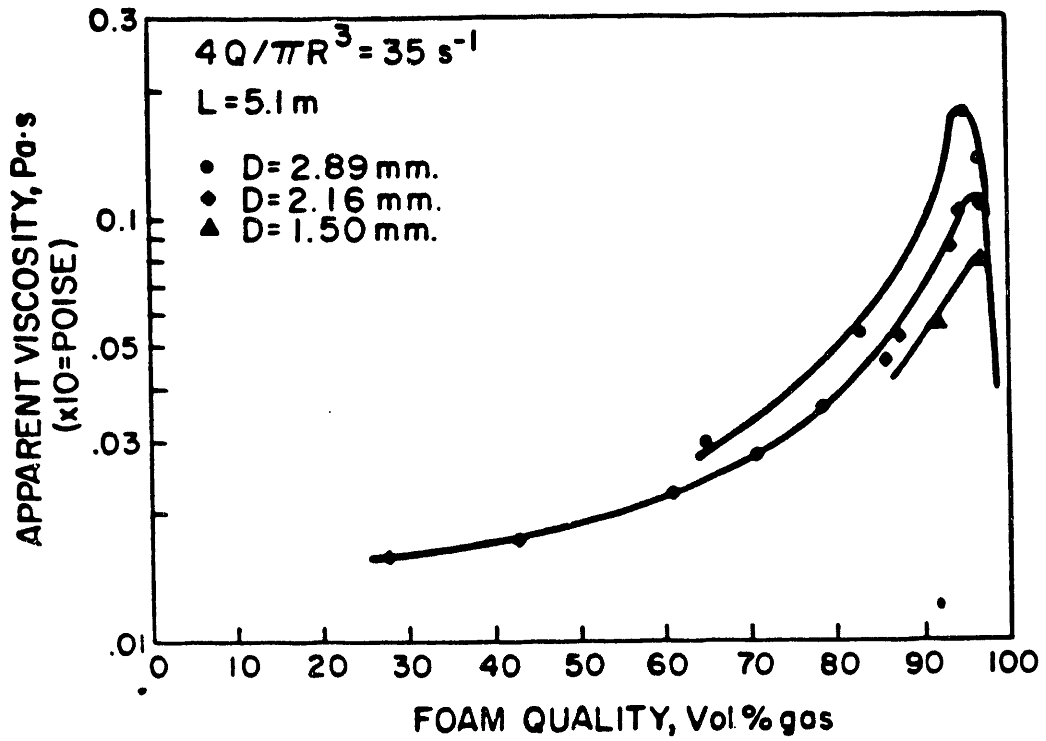


Figure 2.7: Holbrook (1981), Gas Resistance Increases with Foam Quality

The results of Dilgren (1982) and Jensen and Friedmann (1987), Figure 2.9, who checked quality effects of steam foams in porous media, show that foam resistance is inversely proportional to foam quality. These results require transport to be by the MAB mode, an expected situation as most laboratory steam foam applications use extremely high steam volume fractions. For example, Dilgren checked quality effects using 50% and 20% steam mass fractions. These mass fractions correspond to steam volume fractions (at 84 psia) of 99.6 and 98.7 percent respectively (the exact pressure used by Dilgren was not recorded). Such very high steam volume fractions almost completely preclude BTT so the results are as expected. Actually, the relatively small reported increases in pressure gradient of from 5 to 50 times the no foam values are indicative of very weak foams indeed. The use of low quality gas foams at the concentrations used by these researchers can give apparent viscosity increases on the order of 1000 times the no foam cases. In fact, if not for the stabilizing affects of nitrogen, high surfactant concentration, and large permeabilities (4 D, 1.0 wt% of Siponate DS-10 for Dilgren; 30 D , 0.5 wt% [exact type not recored] for Jensen), it is doubtful that even these relatively meager increases would have been attained. At 1600, 2000, 2400, and 2800 psia — more representative of field conditions — the gas volume fractions for 50% steam mass quality are 90, 88, 83, and 77 percent. These lower volume fractions would be more conducive to foam stability assuming that the surfactant is injected in the liquid fraction of the steam, which means that more mass of surfactant is injected as the steam quality decreases. If the liquid fraction of the steam does not contain surfactant then decreasing steam quality will only dilute and wash away the surfactant (results from this report), with a resulting detrimental effect. In steam foam studies the increased stability accompanying a reduction in steam mass fraction is probably not the result of improved stability from reduced capillary suction pressure but rather a result of the large relative change in surfactant mass being injected when changing the steam mass fractions. For example, when Dilgren went from 50 to 20% steam mass fraction the amount of injected liquid surfactant solution changed from 1.5 to 2.4 milliliter per minute. This relative increase (60%) is felt to be the reason for the typical results of Dilgren, and Jensen and Friedmann.

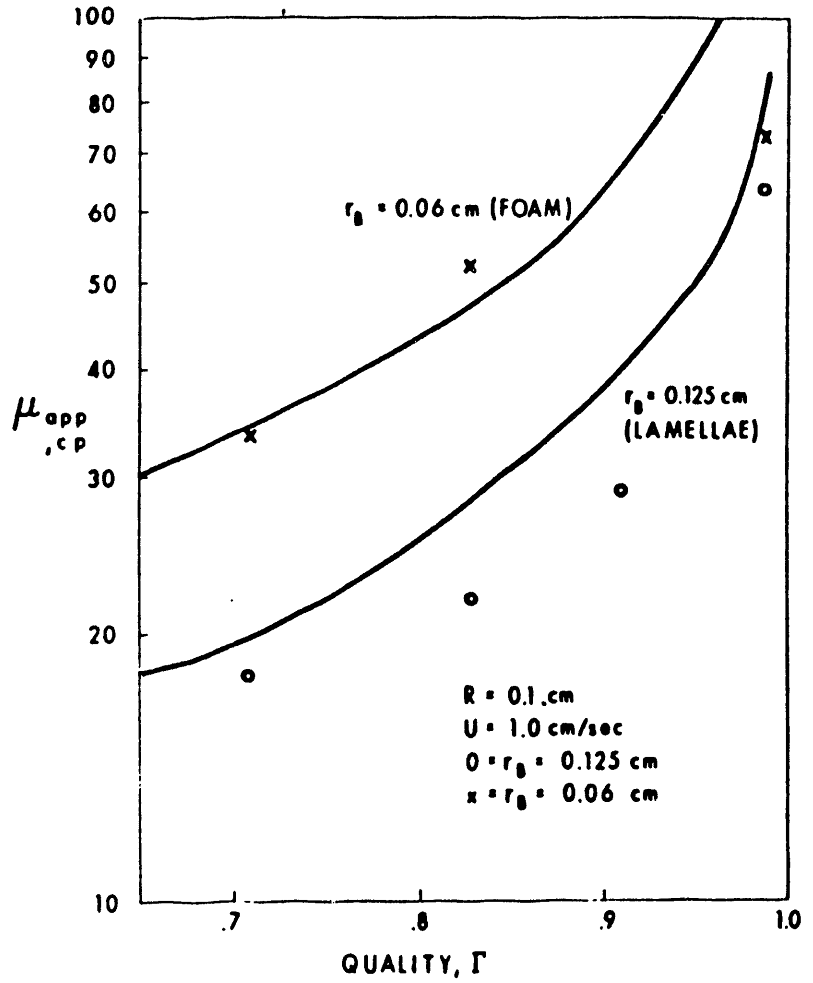


Figure 2.8: Hirasaki and Lawson (1985), Gas Resistance Increases with Foam Quality

The results of Huh and Handy (1989), Figure 2.10, can also be considered by the transport mode concept. For their steady state procedure they generated foam in-situ by injecting Suntech IV solution (0.02, 0.2, 1.0 wt%) and nitrogen gas into Berea sandstones (10" x 2"; 400 to 600 md) that had been presaturated with surfactant solution. Their result that foam resistance is slightly inversely proportional to in-situ gas saturation requires MAB flow for consistency with the concept of transport mode. This (MAB) is reasonable as the fairly low permeabilities used would not be expected to support BTT except at low qualities. This assertion is strengthened by Trienen's results and in fact many of the results by Huh and Handy are similar to those by Treinen. Below a critical in-situ gas saturation of 35 to 40% all gas flow was essentially blocked. This result is understandable since the lower gas saturation means higher surfactant availability and reduced capillary suction pressure. Had they forced gas to flow at the very low gas saturations it is expected that they would have found foam resistance to be proportional to gas saturation, indicating foam flow by BTT. This implies that the critical gas saturation marks the onset of the MAB mode and corresponds to the break point previously discussed.

Bernard and Holm (1964) used Berea cores (100 to 250 md; 6 to 30 inches long; 20% porosity) and sandpacks (3 to 150 D; 1 to 30 ft long; 40% porosity) with a steady state procedure where surfactant (type not disclosed) and nitrogen gas were injected continuously. In a 3.9 D sandpack they compared foam strength as a function of in-situ gas saturation at three concentrations (0.01, 0.1, 1.0 wt%) of surfactant. The critical gas saturation or, as conjectured in the previous paragraph, the onset of MAB occurs at higher in-situ gas saturations depending upon the surfactant concentration. At 0.01 wt% the critical gas saturation is 28%, at 0.1 wt% it is 55%, and at 1.0 wt% it is not apparent even at 77% in-situ gas saturation. These results, Figure 2.11 show that higher

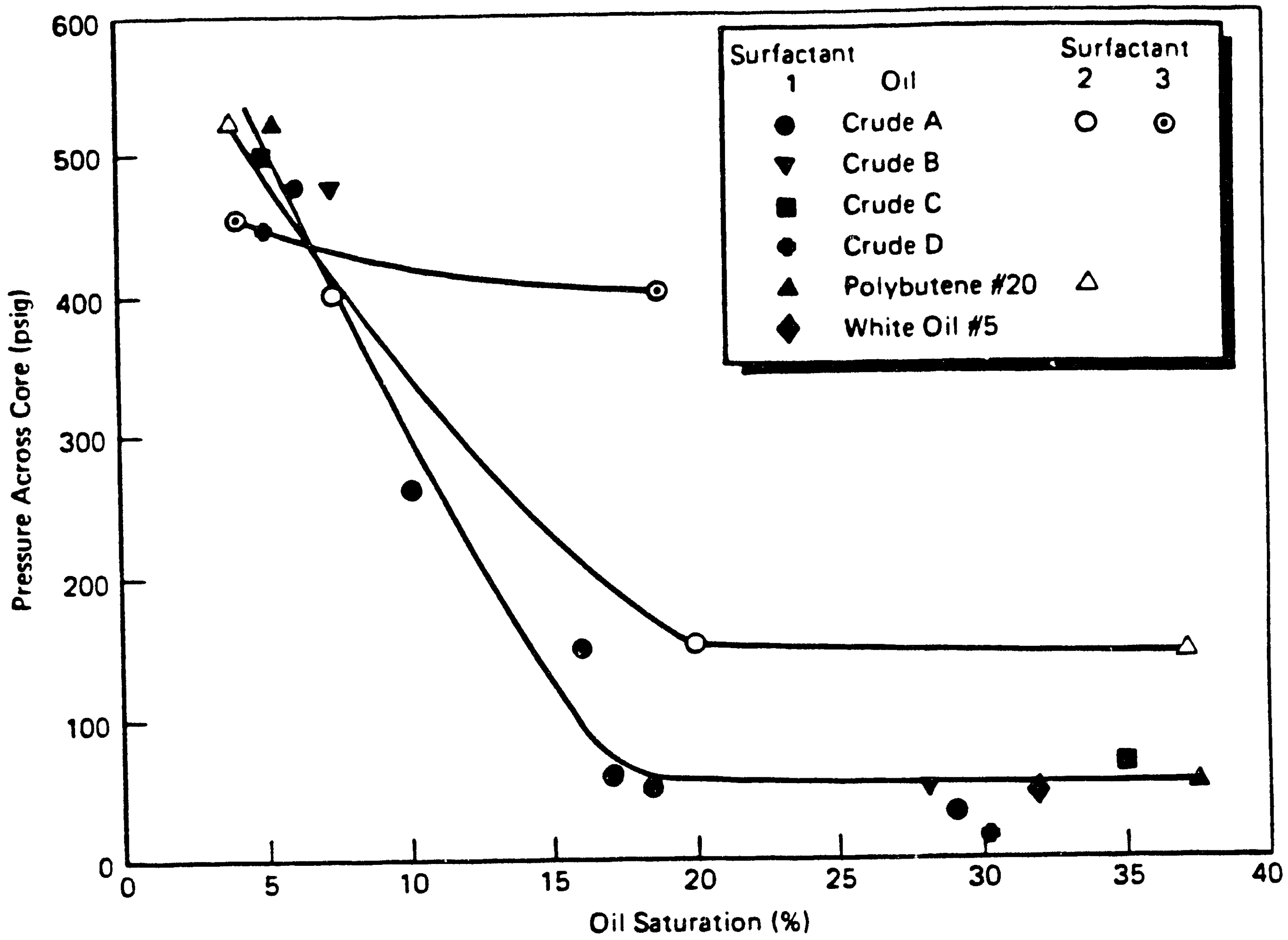


Figure 2.9: Jensen and Friedmann (1987), Gas Resistance Decreases with Steam Quality

concentrations can withstand larger gas satuations and capillary suction before breaking down into a MAB mode of transport. The logical conclusion is that at lower permeabilities, keeping concentration constant, the increased capillary suction pressure would force the onset of MAB (critical gas saturation) to occur at lower and lower gas saturations. In fact they proved this to be the case using a 225 md Berea core, a 3350 md sandpack, and a 146 D sandpack, Figure 2.2. The fact that the critical gas saturation for the 225 md core and 3350 md sandpack are practically identical is probably a result of the lack of measurement sensitivity below about 0.5 millidarcy, which corresponds to very low rates of gas production. This is apparent from the scatter in the data for the 146 D sandpack. The different slopes may be proportional to the rate of coalescence, with large slopes representing a fewer percentage of generated lamellae that are effective flow barriers.

The results of de Vries and Wit (1990), Figure 2.12, in sandpacks of 4.2 and 1.2 D show both increasing and decreasing foam resistance as the injected (pregenerated) foam quality is increased, with a break point delineating the transition between the increasing and decreasing trends. Based upon their sandpack studies they formulate a capillary model that predicts such a break point. They postulate that below the break point both foam filled and water filled capillaries exist, at the break point only foam filled capillaries exist, and above the break point gas filled capillaries appear.

One final comparison. Marsden and Khan (1966) obtained results opposite to those of Fried (1961) even though the same type of viscometer, a Fann VG Meter, was used. Fried placed a measured volume of surfactant solution into the Meter's cup, generated foam with a mixer, then

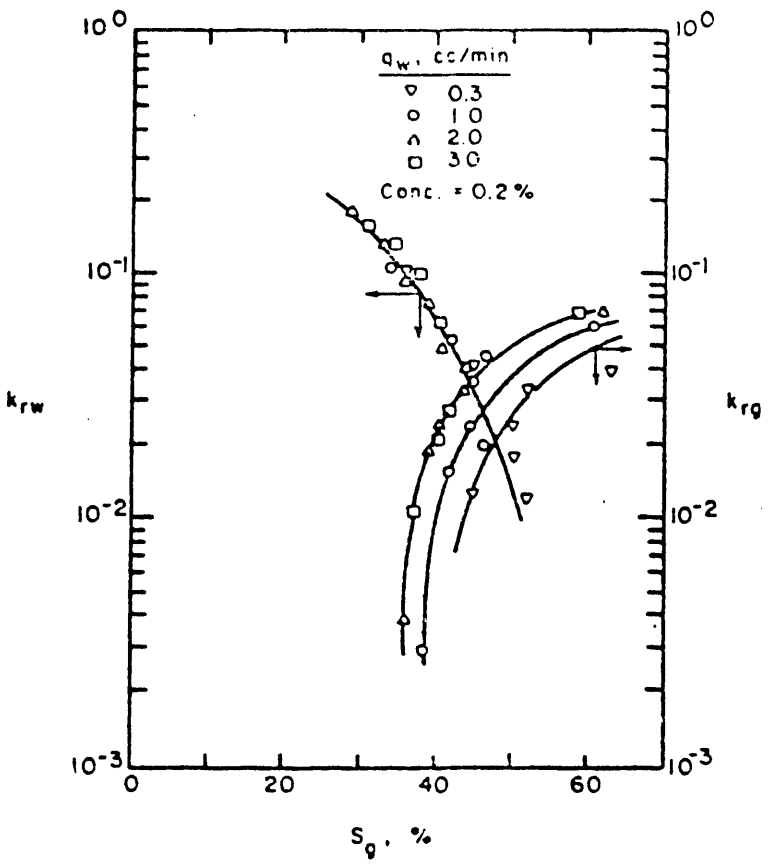


Figure 2.10: Huh and Handy (1989), Gas Resistance Decreases with In-Situ Gas Saturation

measured foam viscosity as the foam drained. His result that apparent viscosity decreases with drainage percent is tantamount to finding viscosity being inversely proportional to foam quality, which understandably reflects the reduced stability of the foam as surfactant drains from the lamellae films, and the reduced resistance of the larger bubbles that result from coalescence. Marsden and Khan, however, using the same type of Meter find apparent viscosity being proportional to quality. Their results are also understandable. Their procedure of continuously injecting foam into and through the Meter's viscometer cup sufficiently reduced the foam retention time to preclude coalescence even for the highest qualities used (about 92%). Since coalescence did not occur during viscosity measurements, foam stability differences between low and high quality foams were unimportant. What was important was that the bubble density increased with quality. This increased bubble density resulted in viscosity increasing with quality. Put succintly, Fried's bubble texture became coarser with foam quality increases while Marsden and Khan's texture became finer with quality increases. The different results actually reflect the identical effect of texture, in agreement with Hirasaki and Lawson (1985) who show that finer textures cause higher viscosities.

The above interpretations of the data from various researchers, summarized in Table 2.2, gives further credence to the transport mode concept since contradicting reports can be reconciled. There is also some indication that the critical gas saturations and the break points seen by many researchers may be synonymous with the onset of the MAB mode. The following sections consider oil and injection technique effects.

2.7 Oil Effects

The detrimental effect of oil upon the strength and stability of foam in porous media has been observed and corroborated often since the early studies of Bernard and Holm (1964), with

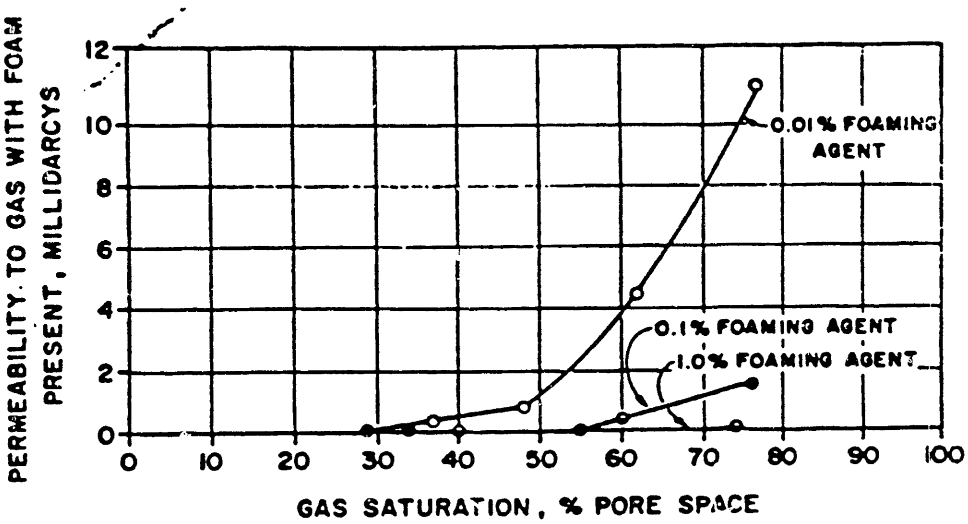


Figure 2.11: Bernard and Holm (1964), Gas Resistance Increases with Concentration

Table 2.2: Summary of Quality Effects

Reference	Injection Quality (%)	Absolute Permeability (Darcy)	Surfactant Type	Surfactant Concentration (wt%)	Expected Mode	Expected Result	Actual Result
Treinen	70-90	7	Suntech IV	0.005	MAB	$R \propto 1/\Gamma$	$R \propto 1/\Gamma$
Treinen	70-90	7	Suntech IV	0.010	MAB	$R \propto 1/\Gamma$	$R \propto 1/\Gamma$
Treinen	70-90	7	Suntech IV	0.05-0.30	?	?	$R \propto 1/\Gamma$
Holm	75-95	5	OK Liquid	0.100	?	?	$R \propto \Gamma$
Kovalchuk	54-94	34-299	Arquad12-50	1.00	BTT	$R \propto \Gamma$	$R \propto \Gamma$
Robin		140	?	1.00	BTT	$R \propto \Gamma$	$R \propto \Gamma$
Holbrook	30-97	cap-tube	AlipalCD-128	0.50	BTT	$R \propto \Gamma$	$R \propto \Gamma$
Hirasaki	70-99	cap-tube	SiponateDS10	1.00	BTT	$R \propto \Gamma$	$R \propto \Gamma$
Dilgren	99+	4	SiponateDS10	1.00	MAB	$R \propto 1/\Gamma$	$R \propto 1/\Gamma$
Jensen	99+	30	?	0.50	MAB	$R \propto 1/\Gamma$	$R \propto 1/\Gamma$

pertinent factors including : oil type

Raza (1970), Lau and O'Brien (1988), Suffridge et al (1989);

oil saturation

Jensen and Friedmann (1987), Yang and Reed (1989);

surfactant type

Bernard and Holm (1964), Robin (1985), Nikolov et al (1986), Jensen and Friedmann (1987), Suffridge et al (1989);

surfactant concentration

Nikolov et al (1986);

partitioning between phases

Al-Khafaji et al (1982);

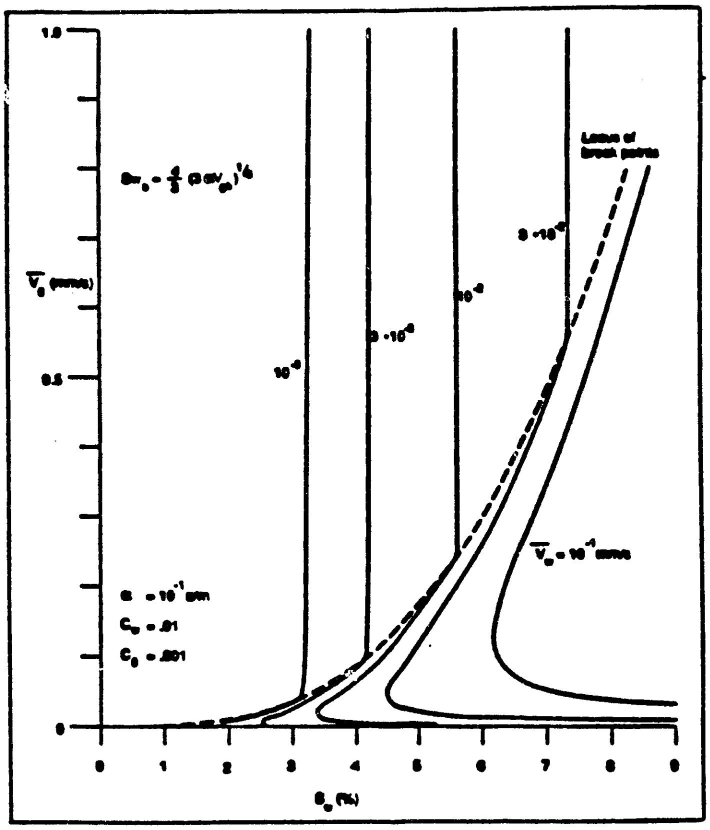


Figure 2.12: de Vries and Wit (1990), Observed Break-Points

wettability alterations

Huh et al (1989), Suffridge et al (1989), Sanchez and Hazlett (1989),

and; electrolyte concentration

Nikolov et al (1986), Lau and O'Brien (1988).

So, except for unconventional surfactants where the oleophilic hydrocarbon tail has been made oleophobic through substitution, it is well established that oil hinders the ability of foam to reduce gas permeability and gas trapping

Bernard et al (1965), Raza (1970), Hanssen and Dalland (1990).

Nevertheless, much disagreement exists in regard to the importance of the above stated factors and in regard to the foam destabilization mechanisms. Some examples of the existing disagreements follow directly below.

Using two nonpolar oils and simultaneously injecting surfactant and nitrogen, Lau and O'Brien (1988) find that a spreading oil (30/70 mix of Nujol mineral oil and Shell-Sol 71) increases the time for foam generation, decreases the speed of foam propagation, and breaks a foam faster than a nonspreading oil (hexadecane). However Manlowe and Radke (1988), using pregenerated foam, dispute the generality of the oil spreading mechanism as the two oils they used showed the opposite effect, with the nonspreading hexane being more destabilizing than the spreading dodecane. Testing 48 surfactants with crude oil, Hanssen and Dalland (1990) find that only those oil surfactant combinations resulting in nonspreading oil are able to block gas. Yet some nonspreading systems did not block gas, leading them to infer that nonspreading is necessary but not sufficient. These conflicting results show that some important factors are being overlooked. Perhaps the only safe assessment is that separate oils can destabilize a given surfactant foam to different degrees. Finding such a result, Suffridge et al contend that oils of lower alkane chain length are more adverse to foam volume as a C11 oil (Soltrol-130) significantly affected foam volume but a C18 oil did not (Blandol). The crude oil (West Texas Crude) used by Suffridge et al had an effect intermediate between the C11 and C18 oils. However Raza (1970) finds that crude oil (type not specified) reduces foam quality more than a C10 - C12 refined oil and that a crude pentane mixture results in a higher foam quality than from a crude alone. So the results of Raza and the results of Suffridge et al are at odds with each other, which again shows that some critical factors are being missed. The results imply that attempts to explain oil foam interactions require a thorough knowledge of the chemical nature of both the oil and the surfactant.

To some degree the importance of oil type is reduced by the results of Jensen and Friedmann (1987) and Yang and Reed (1989) who show that the oil saturation level is the predominant influence. These researchers find only minimal foam generation for conventional surfactants when the residual oil saturation (ROS) is above about 15%, and find strong foam generation only when ROS is below about 8 percent. The oil used by Yang and Reed was decane, while Jensen and Friedmann used four crude and two refined oils. The only case studied which might at first not support the above findings is that of Lau and O'Brien. They started with 89% oil saturation in their medium and did not report trouble in generating foam. However, closer inspection of their data, Figure 2.13, for foam front location, pressure drop, and average oil saturation indicates that foam was not generated until oil saturation had dropped significantly. At foam breakthrough, for example, the ROS in their model was essentially zero, implying that low ROS's were required to generate and propagate foam. So while various oil surfactant combinations may result in foams with stability differences when ROS is below about 15%, above such oil saturation levels they are all equaly ineffective. This has led to the testing of unconventional surfactants which have proven to be quite oil insensitive (Robin [1985], Jensen and Friedmann [1987], Suffridge et al [1989]). Such surfactants, being neither oleophilic nor hydrophilic, are postulated (Hanssen and Dalland [1990]) to make pseudoemulsion films (Nikolov et al [1986]) separating gas and oil appear like foam films separating gas bubbles.

The success of unconventional surfactants would imply that oil partitioning is an important criteria when considering the instability of conventional surfactants in the presence of oil. Serious doubt, however, has been voiced by Robin (1985) who states that the amount of surfactant lost to an oil phase is insufficient to explain the large observed reductions in foam stability. The degree of partitioning for Suntech IV into a Kern River 12 degree API crude oil has been quantified by Al-Khafaji et al (1982), who show significant surfactant losses at lower surfactant concentrations (30% at 0.5 wt%), but more moderate ones at higher concentrations (18% at 1.0 wt%). Jensen and Friedmann (1987), using 0.5 wt% solutions, find partitioning from 0.9 to 16.6% depending upon the surfactant and oil used, with the greatest loss occuring for crude oils. The highest partitioning recorded by Jenson and Friedmann was for their surfactant (type not specified) that was oil insensitive and formed a strong foam in the presence of oil. This surprising result, along with the often large reductions in foam strength associated with small surfactant loss, corroborates the opinion of Robin and all but eliminates the notion that oil phase related reductions in foam strength are due to surfactant losses into the bulk of the the oleic phase.

While current research has caused phase partitioning to fall into disfavor as a plausible explanation for foam strength reduction in the presence of oil, current research (Hirasaki [1991], Buckley et al [1989], Morrow [1990]) has shown that wettability alterations are more common and important than previously believed (see previous discussion on wettability). Knowledge of rock property changes occuring from oil or surfactant contact is critical since high water saturation and water wettability is necessary to generate and maintain a strong foam (Jimenez and Radke [1988]). This water wetting requirement is confirmed by Suffridge et al and Huh et al, with the data of

Suffridge et al being especially convincing as they compare two similar Berea cores. One of their cores was unaltered while the other was made intermediate to oil wet by Quilon treatment. Both Suffridge et al and Huh et al find reduced foam strength with increased oil wetting. Concerning the ability of surfactant to alter wettability, Sanchez and Hazlett argue as such when explaining foam formation in oil wet (silanated) beads packs and when explaining shifts in liquid phase relative permeability in the oil wet medium upon introduction of surfactant. They did not observe relative permeability shifts and foam formation when oil was present in the packs, indicating that gains in water wettability by surfactant addition are offset by the presence of oil. A suggested study would use oil insensitive surfactant and compare results from (1) a water wet medium without an oil phase (2) a water wet medium with an oil phase (3) an oil wet medium without an oil phase, and (4) an oil wet medium with an oil phase. Such an experiment would show whether a nonconventional surfactant can change the wettability of an oil wet medium in the presence of oil.

The preceeding discussion stresses the need for a water wet medium but it does not get to the root of oil related destabilization. Simple bulk tests (Bernard and Holm [1964], Hanssen and Dalland [1990], Suffridge et al [1989], Hudgins and Chung [1990]) prove, irrespective of wetting arguments, that some other factor is responsible. One possibility is the oil spreading mechanism advanced by Lau and O'Brien (1988), which is based upon their results and is strengthened by the results of others (Hanssen and Dalland [1990]; Schramm et al [1990]). However Manlowe and Radke (1988) show that it isn't entirely a general phenomenon. As an alternative they suggest that stabilization of the pseudoemulsion film (Nikolov et al [1986]) separating oil and gas is the key to strong foam maintenance since, they argue, film rupture must precede oil spreading. Neglecting solvation forces and adopting the plane model of Reynolds (see Manlowe and Radke) they calculate pseudoemulsion film drainage times that agree with experimentally observed collapse times. Unfortunately, their accuracy is limited by their ability to properly estimate physical parameters, so they caution against exact comparison of theory and experimental data. Their method finds that drainage time increases with contact area, in complete agreement with DLVO theory, but in disagreement with the experimental observations of Nikolov et al who find that small oil droplets have thicker and more stable pseudoemulsion films. Nikolov et al suggest that the large surface curvature of small drops magnifies surface tension (Marangoni) gradients which resist film thinning. Perhaps the addition of surface tension gradient effects and oil spreading effects to the model of Manlowe and Radke would provide the complete picture needed to reconcile existing data. Nevertheless one additional mechanism is offered.

A possible mechanism can be advanced based upon the idea of surfactant loss. This view is not meant to suggest partitioning as most measured values are understandably low considering the hydrophilic anionic head of conventional surfactants, i.e. the oil would need to have polar components to stabilize such a charge in the mass of oil itself. Jensen and Friedmann's (1987) results strengthen this view since as only 0.9 to 3.8% of surfactant partitioned into the synthetic oils (these oils strongly destabilized foam), while the partitioning into the crude oils was up to 16.6% . Yet, the hydrophobic tail of conventional surfactants would be preferentially stable in oil, not in either water or gas. The implications are that: (1) a great deal of surfactant should be stable at water-oil interfaces; (2) such stability of surfactant at water-oil interfaces should increase with increasing salt concentration since sodium would enable close packing of surfactant; (3) in the presence of oil, the addition of salt would be detrimental to foam stability, even though some salt (less than 5 wt%) is advantageous for foams in the absence of oil; (4) oil probably destabilizes foam by scavanging surfactant from pseudoemulsion films separating oil and gas; (5) small droplets of oil should be less destabilizing since their reduced surface areas can adsorb (scavange) less surfactant from a given pseudoemulsion film, and; (6) spreading oils should be detrimental since oil surface area is significantly increased.

The above proposed mechanism is based on the idea that a conventional surfactant, having a hydrophilic head and a hydrophobic tail, would be much more stable with the tail in oil rather than in gas. Such a stability preference, which could be termed preferential adsorption onto oil, should cause the eventual destruction of all pseudoemulsion films and the destruction of all foam. The transfer of surfactant both to and from either oil-water or gas-water interfaces should be a dynamic equilibrium type process. If it has not already been done so by surface chemists then proving that a large amount of surfactant resides at oil-water interfaces would aid in understanding the destabilization of foam by oil.

Aside from destabilization mechanisms, however, a practical solution to foam generation in porous medium in the presence of oil would employ a mixture of nonconventional and conventional (NCC) surfactants as suggested by Holcomb et al (1981). Such a surfactant blend would foam in the presence of oil, yet form an even stronger foam in oil swept zones. One important implication is that an economic advantage might result by NCC surfactant injection at an early stage of steam operations. Laboratory experiments employing a 3-D model either corroborating or refuting such a possibility would be very useful in determining field application.

2.8 Injection Technique Effects: SAG vs SIS

A short review of Hamida's (1990) experimental work in comparison with the results of Demiral (Runs 1 to 3 of the current report) serves to highlight the importance of injection technique. Using a simultaneous injection scheme (SIS), Hamida injected surfactant, steam, and nitrogen into sandpacks having ROS's of about 12 percent, with the surfactant injection stopping once the desired slug volume (usually 10% PV) had been attained. Hamida did not find an increased pressure drop when compared to the base case having no surfactant even though the injected surfactants (Chaser SD1000, LTS18, AOS1416) gave strong foams in the absence of residual oil. Demiral, however, employing a surfactant alternating gas (SAG) method, did find an increased pressure drop in comparison with the base case. Both used the same model and sandpack.

A reasonable explanation can be made based upon the fact that fluids in porous media flow through separate paths, with the result that steam and surfactant do not mix sufficiently. The explantion is applicable even for the nearly homogeneous conditions that exist in the linear model used by Hamida and Demiral. Additionally, the explanation is consistent with the relative permeability concept where phase permeability is a function only of phase saturation.

Generally, strong capillary forces will segregate fluids in porous media, with the wetting phase occupying smaller pores, the nonwetting phase occupying larger pores, and the intermediate wetting phase occupying intermediate sized pores. With SIS the steam forms a path that is uninterrupted by the introduction of surfactant (i.e., the injected surfactant quickly fills the smaller pores, while the steam continuous in the larger pores). Should some steam and/or surfactant divert into intermediate sized pores, foam formation is inhibited by the increased presence of residual oil found in those pores and by the lower gas flow rates. Therefore the probability for foam formation with SIS is reduced due to insufficient mixing. For SAG, since all gas flow is stopped prior to surfactant injection, surfactant can more evenly distribute into all the pores. Upon reintroduction of steam and nitrogen the gas must flow through surfactant solution to reestablish a path. Therefore the probability for foam formation with SAG is increased as better mixing occurs.

Most of the existing laboratory studies conducted in the presence of oil avoid the mixing issue since such studies use either pregenerated foam or some variation of a SAG method even though most field studies don't (Castanier [1989]; Hirasaki [1989]). Bernard and Holm (1964), for example, saturated a 4 D sandpack with brine solution, flooded with crude oil to residual water, water flooded with brine to residual oil, then injected a 20% PV slug of surfactant (1 wt%) followed by nitrogen, i.e. SAG. Bernard et al (1965) flooded an oil water system (4 D sandpack) to residual oil with 1 wt% surfactant solution then gas flooded, which is equivalent to SAG since the system consisted of an aqueous surfactant phase and an oleic phase before any gas was introduced. Raza (1970) injected a measured volume of surfactant solution into a brine oil saturated porous medium then injected gas, ie SAG. Nikolov et al (1986) injected gas into a preequilibrated surfactant oil system, which is equivalent to SAG. Yang and Reed (1988) used a 'dual bank' injection: 3 to 5 PV of surfactant solution followed by 2 PV of CO2, i.e. SAG. Hudgins and Chung waterflooded to a ROS of 24%, followed by various alternating injections of surfactant slugs and nitrogen, i.e. SAG. Hanssen and Dalland (1990) used glass beads packed in 200 cm long columns, then generated foam by gas displacing surfactant at constant pressure, again SAG. The reviewed researchers who used pregenerated foam were Manlowe and Radke (1988), Shramm et al (1990), and Jensen and Friedmann (1987). So all the above researchers ensured good mixing either by forcing the injected gas to make a path through an aqueous surfactant phase or by injecting pregenerated foam.

There are some laboratory studies where the surfactant is injected simultaneously with the steam as in typical field studies. In such studies, in contrast to those by Hamida, the conditions ensured good mixing. For example, Dilgren et al (1982) simultaneously injected nitrogen, surfactant solution, and steam into a pack having 30% oil saturation. They obtained very good results using 50% quality steam (1.5 ml/min cwe steam; 1.5 ml/min surfactant solution). If Hamida had scaled injection procedure to match Dilgren on a PV basis the surfactant and steam rates would have increased by four and one half times, which might have made the necessary difference between foam or no foam. Jensen and Friedmann (1987) had successful steam foam displacements employing a simultaneous injection scheme (SIS), however they injected extremely high rates (1200 g/min cwe of steam and 42 sl/min of nitrogen) and had two static mixers to homogenize the gas, steam, and surfactant solution. Again, mixing was ensured.

The above discussion suggests that high rates aid mixing and, therefore, foam generation. The results of Huh et al (1989) indicate that mixing can be aided by heterogeneity as well. They find that the most important factors in the in-situ generation of foam are mixing of fluids and the aspect ratio of the pore structure, with the more heterogeneous models promoting better mixing and subsequent generation of foam bubbles. Marsden et al (1967) also stress the need for thorough mixing of gas and liquid.

So, *incomplete mixing resulting from the injection technique and the lack of heterogeneity* is a plausible explanation for the failure of SIS to generate a foam in the presence of residual oil (Hamida [1990]). Conversely, *improved mixing resulting from steam and nitrogen having to constantly reestablish a path through a surfactant phase* is a plausible explanation for the success of SAG in generating a foam in the presence of residual oil (Demiral, RUNS 1 to 3 of this report).

Incomplete mixing can also explain why, even in the absence of oil, 5 to 10 minutes of surfactant injection were required by Hamida before a pressure response was noted. It can also explain why Isaacs et al (1988), using a SIS method, needed to inject upto 3 PV of surfactant into a 12 D sandpack devoid of residual oil before obtaining a sudden increase in pressure drop across the pack.

This concludes the literature survey. The following sections discuss the experimental equipment, the results, and the conclusions.

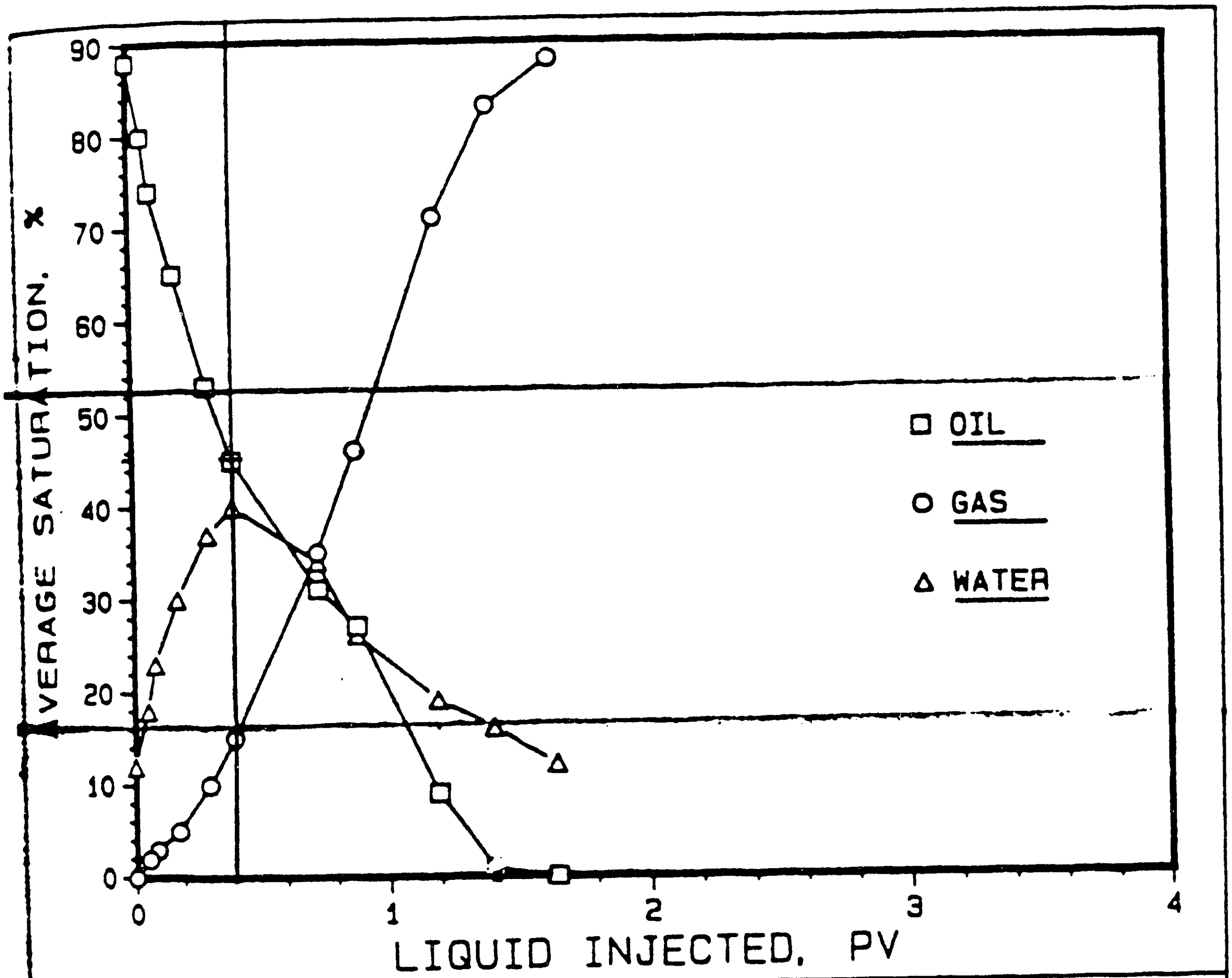


Fig. 3—Average fluid saturations during foam displacement with hexadecane, a nonspreading oil.

Figure 2.13: Lau and O'Brien (1988), Fluid Saturations During Foam Displacement

3. Experimental Procedure and Equipment

3.1 Linear Sandpack and Supporting Equipment

A schematic of the linear model and supporting equipment is shown in Figure 3.1. The model is a cylindrical stainless steel tube having a 6 ft. length, a 2.16 in. inside diameter, and a 2.25 in. outside diameter. It is packed with clean Ottawa sand. The resulting porosity is 35% and the permeability is 95 Darcy. The 21 thermocouples along the sandpack are separated between 2 in. near the inlet to 8 in. near the outlet. Their location alternates between being at the center or being 0.5 in. from the top of the pack. Five taps at 0, 16, 32, 52, and 72 inches from the inlet allow for pressure drops to be recorded across four separate sections. Seven thin film heat flux sensors provide energy loss information, from which the overall heat transfer coefficient and, eventually, the steam quality along the sandpack can be determined. Four of the heat flux sensors are at the top of the tube (14, 26, 38, and 57 inches from the inlet). The other 3 are at the bottom, left and right side of the tube at a distance of 26 inches from the inlet. Fluid injection is handled with four pumps, including a GE 1/4 HP pump and three Constametric Model III pumps. Of the Constametric types, one is exclusively for input to the steam generator, a second is for low rate distilled water injection, and a third is for injection of either surfactant or cleaning fluid. The GE pump provides for high rate distilled water flushing. In addition: an IBM-XT computer via an HP Model 3497A data acquisition system records pressure and temperature information from 4 transducers and 24 thermocouples (21 along the pack, one in the steam generator, and one at the inlet and outlet flow lines); a Marshall Model #1056 tubular furnace generates steam; a Matheson Model 8141 mass flowmeter controls nitrogen rate, and; strip chart recorders provide continuous analog output of pressure drops and flow rates.

3.2 Experimental Procedure

3.2.1 Prepartion Prior to Run

Day 1: Inject crude oil into the water saturated sandpack until breakthrough (Mobil Baming Lease, Newport Field, 9/14/90; 20 psi back pressure [BP]). Continue injection for an additional 100 ml to ensure that water production has ceased. Record the total water production and leave overnight at residual water conditions.
Day 2: Inject steam until breakthrough (100% mass quality; 4ml/min cold water equivalent (CWE); 70 psi BP). Continue injection for an additional one to two hours until all traces of oil production has stopped. Record total oil production. Inject water to cool system and leave model overnight with only water and residual oil. On Day 3 an experiment is run.

3.2.2 Procedure During a Run

Preparation: Inject steam until breakthrough at quality conditions to be used during the run and with 70 psi BP. After breakthrough of steam, inject nitrogen, while continuing steam, for an additional hour Total time is approximately 4hours.
Slug Injection: Stop steam and nitrogen and inject surfactant solution (Enordet AOS 2024) at 10 ml per minute. Upon completion of slug, resume injection of steam and

nitrogen. Additional slugs are injected similarly, with approximately one hour between slugs.

Shut Down: Upon completion of experiment, flush sandpack with 4 pore volumes (PV) of water. (note: 1 PV is 1500 ml)

3.2.3 Procedure Between Runs

Day 1: Inject 6 PV of water, then 1.5 PV of mineral spirits.

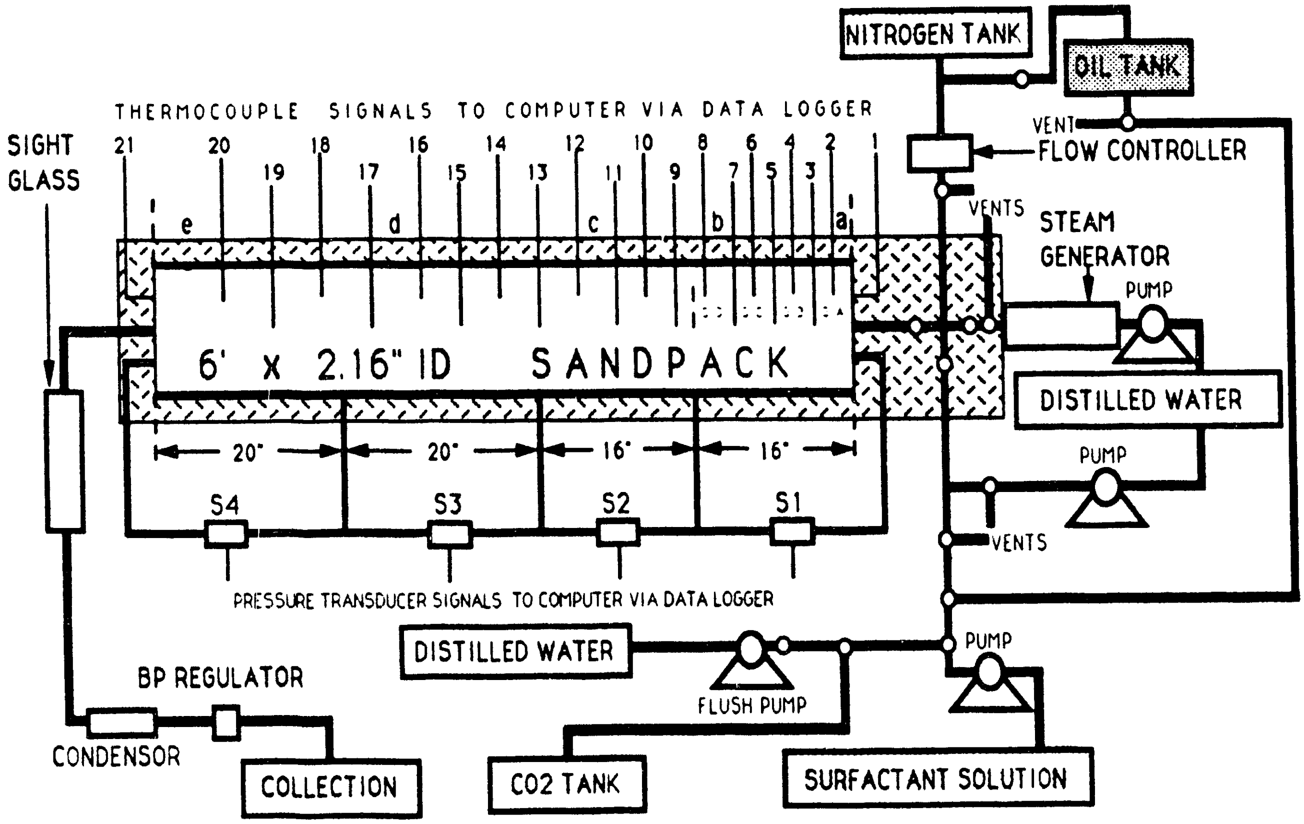
Day 2: Inject 0.5 PV of mineral spirits, 1.5 PV of warm (27 C) tert-butyl-alcohol (TBA), and 4 PV of hot (60 C) distilled water. Follow with CO2 (43 psi inlet, 40 psi BP) for one hour, then flush with 5 PV distilled water. System cleaning is complete.

3.3 Experimental Conditions

Table 3.1 lists the experiments performed and the conditions applying. Included are the previously unpublished runs made by M.R.B. Demiral (Runs 1, 2, and 3).

Table 3.1: Summary of Experimental Conditions

Run	Slug Conc.	Slug Size	Steam Quality
1	1.0 wt%	10% PV	100%
2	zero	10% PV	100%
3	1.0 wt%	5% PV	100%
4	1.0 wt%	1% - 5% PV	100%
5	0.1 wt%	10% PV	100%
6a	0.1 wt%	10% PV	40% - 100%
6b	0.1 wt%	10% PV	100%
6c	0.1 wt%	10% PV	100% - 40%
7 (repeat of 6a)	0.1 wt%	10% PV	40% - 100%



Thermocouple Separation
a = 2 in b = 3 in c = 4 in d = 5 in e = 8 in

Figure 3.1: Schematic of Experimental Apparatus

4. Results and Discussion

4.1 RUN 1

For this and all subsequent discussions, S1, S2, S3, and S4 designate the first, second, third, and fourth sections of the sandpack. Similarly, S1A, S1B, S1C, and S1D designate the first, second, third, and fourth sections of section one. These sections and sections are marked on the experimental schematic, Figure 3.1. Section S1A is closest to the steam inlet.

The primary result of RUN 1, Figure 4.1, is that SAG generates and maintaines a foam in the presence of residual oil but SIS does not. The SAG method probably increases mixing between phases as steam and nitrogen, after each slug injection, must reestablish a path through the surfactant phase. Higher flow rates and/or a more heterogeneous medium might generate foam even using SIS and the same model since such measures should also engender better mixing.

In comparison with Hamida's no oil case, Figure 4.2, RUN 1 shows the large destabilizing influence of only 12% residual oil (the calculation of residual oil saturation is given in Appendix A). The signicantly weaker foam is evident from the large reduction in pressure drop across the pack. This large reduction cannot be explained by partitioning losses since such losses are generally not more than 20 percent. The losses also cannot be attributed to rock adsorption since the different responses to the first and second slugs for Hamida's no oil case, Figure 4.3, are very small. Some other phenomenon must be occuring. One explanation is that large amounts of surfactant reside at oil water interfaces where they are adsorbed. These surfactant molecules are considered to be constantly adsorbing and desorbing in an equilibrium type process that cannot be quenched by simply allowing an oil surfactant system to equilibrate.

The different responses to the first and second slug injections in RUN 1 imply that the oil effects can, up to a limit, be negated. The first slug causes almost no change in pressure drop while the second slug does. Subsequent runs show that the pressure response after Slug2 is a maximum, with additional injections not continuing to give further increases in pressure. Apparently the first slug reduces losses from the second slug. This surfactant loss effect is seen in all runs with the first slug(s) being consummed by adsorption, resulting in stronger responses from subsequent injections.

An additional difference over the no oil case is the reduced response from S4. This reduced response is likely caused by increased oil in that portion of the model, a conclusion based upon the following observations: (1) during flooding to ROS, fewer PV's of steam pass through S4; (2) some degree of override occurs as indicated by heat flux and temperature data, and; (3) additional slug injections (see Figures 4.6 to 4.25 of RUNS 4-7) appear to reduce ROS in S4 to levels matching the other parts of the sandpack. S4 shows the greatest fluctuations in pressure. These fluctuations are due to back pressure variations.

For S1, the relative pressure drop hints that foam strength is reduced in that section. Since the no oil case is similar, the reasons are not considered to be related to the presence of oil. Rather the cause is hypothethized to be from two factors: (1) insufficient wetting phase caused by steam drying of the sandpack, and; (2) wettability alteration, again, from steam drying of the sandpack. Both factors affect S1 the most. To further investigate S1, a modification was made after RUN 6a to allow for pressure drop measurements across sections S1A, S1B, S1C, and S1D. The results from RUNS 6b, 6c, and 7 (Figures 4.18, 4.21, 4.22) confirm the hypothethis as the greatest contribution to the pressure drop across S1 is from S1D, followed by S1C. The contributions from S1A and S1B are zero even for low quality injections, indicating that these sections have altered wettability to the extent of being oil wet. Section S1C's response does change with injection quality and with time of injection, being a greater percentage of the total when injection quality is low and during the first or second injections of high quality steam. This implies that S1C is affected by both low aqueous phase and wettability alterations. One additional observation of S1 is that during slug injection (not steam injection) the pressure drop is typically highest in S1A. This is as it should be.

4.2 RUN 2

RUN 2, Figure 4.4, is a blank experiment without surfactant. The lack of pressure response proves that, for our system, water alternating gas (WAG) cannot increase gas resistance unless surfactant is present, i.e. SAG.

4.3 RUN 3

The proper analysis of RUN 3, Figure 4.5, requires a comparison with RUN 1, Figure 4.1. Such a comparison shows that reducing the slug size (10% in RUN 1; 5% in RUN 3) may not affect the magnitude or duration of the pressure drop. Along similar lines, the splitting of large slugs into several smaller ones can give improved oil recovery (Gopalakhrishnan [1978]) and increased gas resistance (Raza [1970]), all of which imply that a surfactant savings can be realized through proper slug size optimization. Slug size optimization is considered further during RUN 4.

4.4 RUN 4

A salient feature of RUN 4, Figure 4.6, is that there exists a limit below which further reductions in slug size are detrimental (5% PV in this case). Such a minimum confirms the need for both sufficient wetting phase and surfactant, although in this case there seems to be a greater need for more aqueous phase.

The slug size minimum should also represent a need for linear distance through which the gas must establish a path (the mixing idea again). For example, the 5% PV slug minimum found (assuming plug displacement) translates into a 3.6 inch linear distance through which the steam must flow. If the model was 600 ft long, instead of 6 ft long, it is very doubtful that 5% PV (360 linear inches) would be needed to generate foam. Rather, the same linear distance (only 0.05% PV) should probably suffice. If the model was only 0.6 ft long, it is doubtful that a 5% PV (0.36 linear inches) would result in foam generation. Rather, the same linear distance (50% PV) should be needed and anything less would not enable sufficient phase mixing to occur. The above reasoning is a suggested explanation for why Hudgins and Chung (1990) could not generate foam in a 20 inch core using SAG. Their procedure called for 0.1 PV injections (2 inches of linear distance), which were probably not enough to allow for the requisite phase mixing. The results from RUN 5, to be discussed shortly, also indicate the importance of sufficient wetting phase.

Before discussing RUN 5, however, an additional result of RUN 4 is the large relative response observed in S4 after injection of the eleventh slug (compare Figures 4.6 against Figures 4.1 and 4.5 of RUNS 1 and 3). This strong response is likely caused by the washing action of previous slugs, which apparently reduces the ROS in all areas to comparable values.

4.5 RUN 5

RUN 5, Figures 4.7 and 4.8, is compared with RUN 4, Figure 4.6, which once again highlights the importance of the injection method. An analysis of the two runs shows that a given mass of surfactant can cause significantly different pressure responses depending upon whether that mass is injected with a small or large aqueous volume. For example, the first five slugs of each run contain the exact same mass of surfactant (RUN 4: 1.0 wt% in 1.0% PV slugs; Run5: 0.1 wt% in 10.0% PV slugs), yet RUN 5 shows a pressure drop comparable to RUNS 1 and 3 while RUN 4 has no measureable response. The implication is that a more cost effective approach would employ large dilute slugs.

For our conditions, the better cost effectiveness of large dilute injections is especially apparent when comparing this RUN 5 to RUN 1. Such a comparison shows that a factor of 10 reduction in surfactant usage caused only about a 25% reduction in pressure response magnitude.

The result of RUN 5 strengthens the assertion that the minimum slug size of 5% PV found in RUN 4 is more a result of insufficient aqueous phase rather than a result of insufficient surfactant mass. Nevertheless, a comparison of Slug 5 and Slug 7 , Figure 4.8, shows that optimization must consider both slug size and surfactant mass. Notice that the response from S1 almost disappears after the seventh slug injection, even though S2, S3, and S4 remain essentially unchanged. Apparently, the combination of condensation and slug volume provides enough wetting phase to stabilize foam in S2, S3, and S4, but not in S1. Condensation in early sections provide liquid for all subsequent sections, so S4 has the most liquid and S1 the least. Again, the combination wetting phase saturation and surfactant amount is important since in RUNS 3 and 4 (1.0 wt% solution) a 5% PV slug was enough to maintain the response in S1, while in RUN 5 (0.1 wt% solution) a 5% PV slug wasn't, but a 10% PV slug was. Also, the drying action of the steam in S1 may ostensibly result in wettability alterations in that portion of the sandpack since drying will allow oil to contact and adsorb unto the rock.

One unexpected advantage from the selective reduction in S1 is that proper slug optimization for field application may result in a reduced pressure response near the injector well, without a similar reduced response deeper in the reservoir. The reduction near the injector would result from the drying ability of high quality steam near the well, where minimal condensation occurs. Such selective reduction would greatly aid injectivity and be beneficial for foam generation deeper within a reservoir as flow rates would remain higher. Since near well bore regions have large pressure gradients, then inhibiting foam formation near the well but not away from the well could result in a situation where foam generation does not cause noticeable injection pressure increases. This may explain the results of Demiral (3-D model) where foam deep in the model, as verified by CAT scans and temperature profiles changes, did not cause large pressure increases.

The effects of nitrogen and steam rate were minimally investigated in Slug 7. The only statement consistent with all the data is that perturbing the system is detrimental, an effect not expected in field applications since the large volumes would buffer such shocks. The relative effect on S2, S3, and S4 corroborates this opinion as S2 showed the largest effect, followed by S3 and S4. The fact that S1 shows no response after Slug 7 indicates that foam is completely absent in that portion of the pack, confirming previous discussions on that section for this particular run.

4.6 RUN 6

4.6.1 RUN 6a

RUN 6a, examines the effect of steam quality, however, a brief introduction is needed since not all factors are kept constant. For example, the desired steam quality is obtained through addition of the appropriate amount of water (ambient) to the steam phase (Appendix C). In order to keep the total injected energy essentially unchanged the steam generation rate was not varied. However, since latent heat is used to raise the water temperature, steam condensation occurs with the result that the actual steam reaching the sandface is reduced. By comparison with the 100% quality case, the steam reaching the sandface is reduced by 5% at 80% quality, by 12% at 60%

quality, and by 25% at 40% quality. This reduction in injected steam reaching the sandface also explains why the nitrogen mole% of the steam phase increases from 2.9 mole% at 100% quality to 3.9 mole% at 40% quality, even though the nitrogen rate is kept constant. The relative importance of these factors is considered minor because: (1) condensation within the pack is constantly changing the flowing gas volume, regardless of injected quality; (2) the responses from slugs 18 and 19 are strong even though no nitrogen exists other than what might remain from previous injections, and; (3) the results from RUN 6c, which show that under some conditions even quality changes have no affect. Two additional points of introduction: (1) when changing steam quality from 60% to 40%, for example, the new quality is injected for one hour, followed by coinjection of both steam and nitrogen for half and hour, and; 2) the total injection of water plus steam changes with changes in quality, so for the 100% quality case, 4.37 ml/min cwe of steam and zero water is injected; for the 80% quality case, 4.14 ml/min cwe of steam and 1.03 ml/min of water is injected; for the 60% quality case, 3.80 ml/min cwe of steam and 2.54 ml/min of water is injected, and; for the 40% quality case, 3.29 ml/min cwe of steam and 4.94 ml/min of water is injected. All cases have 0.0071 mole/min of Nitrogen gas injection.

The first result of RUN 6a, Figure 4.9, is that five slug injections are needed to obtain even a minor response when steam quality is at 40 percent. Two additional injections evidence the response consistency, which is meager compared with RUN 5 at 100% steam quality, Figure 4.7. The conclusion is that lower steam quality is detrimental to foam generation and stability. Yet numerous laboratory studies (see literature survey) prove that a lower quality is beneficial. The contradiction is removed by noting that those studies kept the surfactant concentration constant in the injected liquid phase. Since the injected liquid phase increased when quality decreased, the amount of surfactant injected also increased when quality decreased. This provided a dual benefit of increased wetting phase and increased surfactant mass. In RUN 6a, however, the surfactant slug has a fixed mass and the injected liquid phase of low quality steam does not have surfactant, so its principal role is to dilute the slug and wash away surfactant previously lost through partitioning and adsorption. For such cases, the subsequent slugs also experience losses since the sites have been washed clean by the water of low quality steam. The result is that each new injection is consummed by adsorption onto oil water interfaces instead of stabilizing foam. This washing effect should also apply in the field, and is another reason for employing the highest quality steam possible when using SAG. The effect is probably not a washing of existing foam, as foam longevity (pressure vs time slopes) differences between qualities is not noticeable. This observation makes sense considering that foam is the nonwetting phase and preferentially resides in different pores than the aqueous phase. It also agrees with the study by Bernard et al ([1965]) who show that existing foam can withstand the erosive effects of water in 4.5 D sandpacks.

Further steam quality changes confirm the above discussion, with the higher pressure resulting from raising quality to 60% (Slugs 8, 9, and 10) beginning a trend that continues as quality is raised to 80% (Slugs 11, 12, and 13) and finally to 100% (Slugs 14, 15, and 16). Further confirmation of the effect was observed when relowering the quality to 40% (Slugs 21, 22, and 23) then raising it back to 100% (Slugs 24 and 25). The relative result is the same as obtained from earlier slugs, however the increased responses reflect that subsequent injections experience fewer losses. Two reasons are offered: (1) the lower ROS in the model during the later slugs probably destabilizes foam to a lesser degree; (2) some surfactant losses are more permanent and not washed clean as easily by the aqueous phase (also refer to the discussion concerning RUN 6c). From this it could be argued that a more cost effective approach would allow time for surfactant to adsorb, diffuse, and partition. The possible benefits of such a 'surfactant soak' could be easily checked.

An additional observation is that response differences between qualities seem to lessen as more slugs are injected, implying that some limiting value is being approached. For example, the relative difference between the responses to Slugs 7 and 16 is larger than between Slugs 23 and

25. This indicates that, given enough injections, the differences between qualities could disappear, with the 40% quality response approaching the 100% quality response. Actually, this was proven to be true in RUN 6c, which began after 30 slug injections and over 50 hours of SAG (cumulative in RUNS 6a and 6b). An explanation for why the pressure responses approach a limiting value, regardless of injected steam quality, is delayed until the discussion of that run.

Nitrogen effects were investigated during Slugs 17, 18, and 19, and also when changing steam quality. The detrimental effect of either adding or removing Nitrogen matches previous results (Slug 7 of RUN 5). The reason for the negative influence of adding Nitrogen is likely the shocking action of introducing it into the model at a slightly elevated pressure (i.e. a laboratory effect). The detrimental effect of removing Nitrogen, once flowing, is not understood, but since a comparison of Slugs 16 and 17 shows the greatest relative influence upon the first and second sections, this effect would probably not be seen in the field. The effect of never reintroducing Nitrogen (Slugs 18 and 19) shows a unique, yet reproducible result. The response in S3 is better without Nitrogen (compare Slugs 16, 18 and 19), while S1, S2, and S4 are worse. This also is not understood, especially as reintroduction of Nitrogen after Slug 20 enhances the pressure drop in all sections.

The response of S4, in agreement with RUN 4, shows the progressive washing of successive slugs.

4.6.2 RUN 6b

After RUN 6a, the steam was condensed with about 2.5 PV of distilled water and allowed to sit for 11 days, followed by steamflooding as per the usual method prior to surfactant injection. However, the results were unusual. By the fourth slug injection of RUN 6b, the responses from S3 and S4 were larger than in previous runs, probably reflecting the lower ROS in the sandpack, but S1 and S2 were much lower than in previous runs. At the time it was considered that perhaps those sections were too dry. To test this, the steam following Slug 5 was reduced to 92% quality (0.3 ml/min of water added). The first two sections did respond to the 5th slug, however the response is not considered to be result of the slight addition of water because: (1) the response of S1 and S2 after Slug 5 is almost immediate, with the amount of additional fluid injected over that time span representing a very small percentage of the 150 ml slug injected; (2) the steam quality was changed several times without any apparent influence (92% quality for 20 min; 100% quality for 12 min; then 80% quality for the duration), and; (3) both RUN 6c and RUN 7, using 100% quality steam, show the usual relative pressure drops between sections. So the reason for the delayed responses from S1 and S2 is not understood and does not seem repeatable.

4.6.3 RUN 6c

After RUN 6b, the steam was condensed with 2.5 PV of distilled water and allowed to sit for 2 days, followed by steamflooding as per the usual method prior to surfactant injection. The results of RUN 6c show that the recorded pressure drops were in accord with previous runs using 100% steam quality. However, of more interest are the differences between this and previous runs.

For this run the response differences between qualities disappeared and the pressure drops from all qualities approached a limiting maximum. As discussed previously, the results of RUN 6a had hinted at such an occurance. The following explanation as to why a limiting pressure drop is approached regardless of injected steam quality, once many slugs have been injected, is again based upon fluid distribution in a porous medium. Consider that the medium initially has no surfactant, but only steam, residual water, and residual oil. As surfactant is first introduced, the different paths taken by fluid and gas will tend to keep surfactant from displacing the interstitial water lining the larger pores (preferentially occupied by nonwetting gas and foam). So, when low quality steam is injected the washing effects are pronounced as the injected clean water flushes out the surfactant before it can imbibe, diffuse into, and displace water lining the larger pores where it could be used to stabilize foam. After many slug injections (over 30 had been injected before starting RUN 6c, with only minimal cleaning) the surfactant eventually does imbibe, diffuse into, and displace the interstitial water lining the larger pore walls. For such a case, the clean water associated with low quality steam does not flush out the surfactant from the most essential portions of the pack. So, the distinction between injected qualities disappears. One further note, the above explanation is consistent with the concept of phase relative permeability being a single valued function of phase saturation, which has been shown to be true for the aqueous phase of water foam systems (Holm [1968], Bernard and Holm [1965], Huh and Handy [1989]).

A further check for the above explanation would be to saturate the model with surfactant solution prior to steaming out. If at that point the quality effect seen in RUN 6a (and RUN 7) disappears, then the above explanation would be corroborated and would give further credibility to the suggestion that allowing a slug to 'sit' might be advantageous. This has not been attempted at this time.

4.7 RUN 7

RUN 7 is further confirmation of the steam quality effect, with the results being qualitatively in agreement with RUN 6a, although the magnitudes are reduced. After 6 slugs at 40% quality the pressure drops are almost undetectable. However, an immediate change results from the injection of three slugs at 100% quality (Slugs 7, 8, and 9), which is largey eliminated upon dropping quality back to 40% (Slugs 10, 11, and 12).

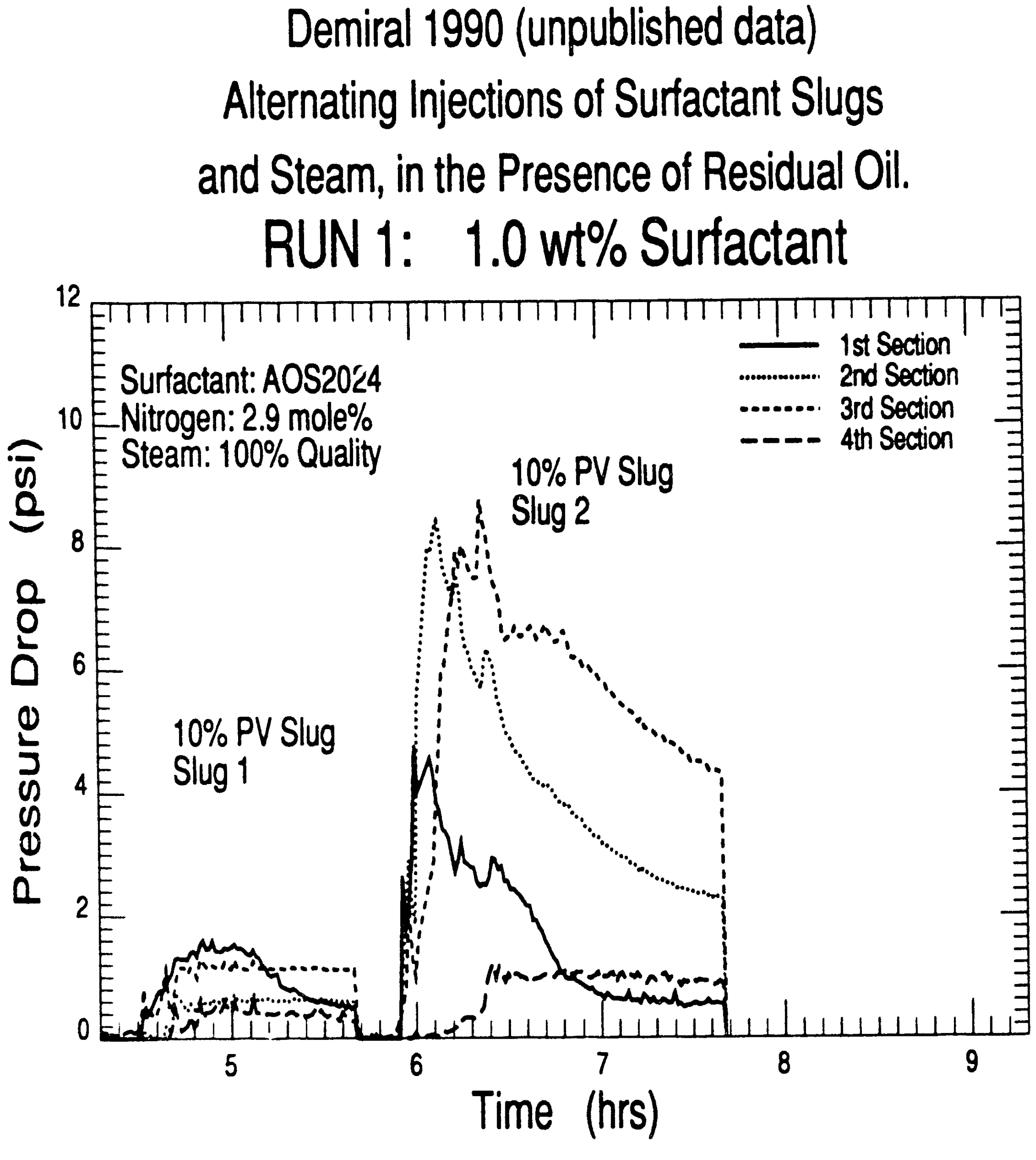


Figure 4.1: RUN 1: Pressure-Drop Across the Sandpack, 100% Quality Steam

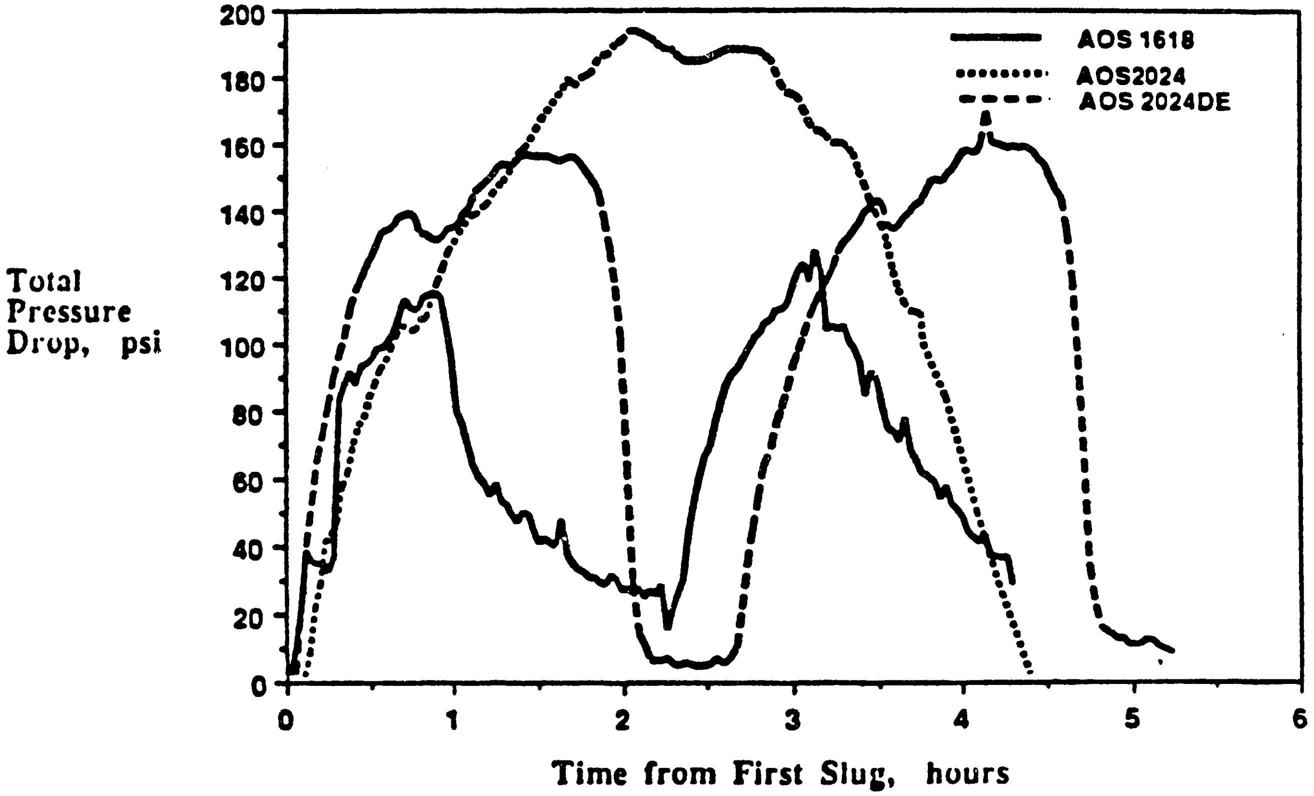


Figure 4.2: Hamida (1990), Pressure-Drop Across the Sandpack, 100% Quality Steam

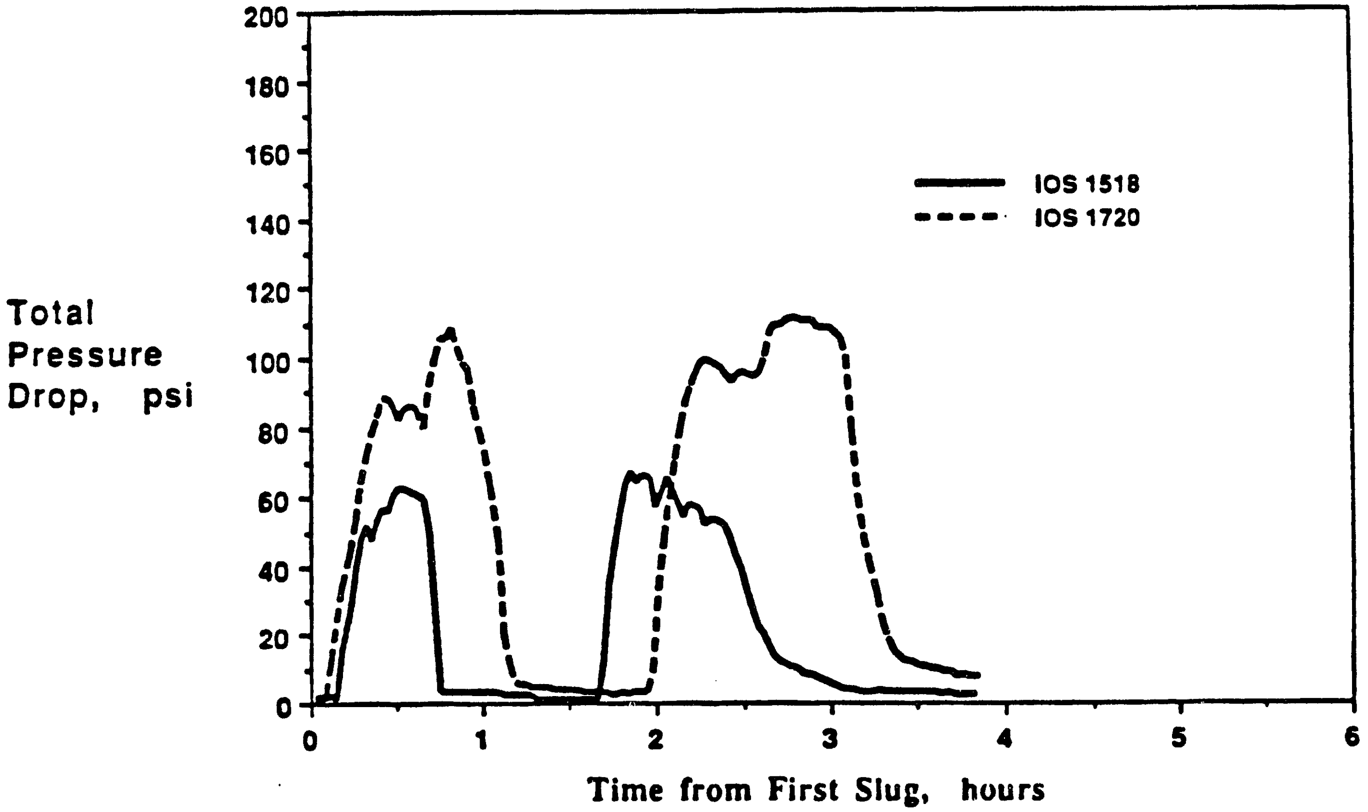


Figure 4.3: Hamida (1990), Comparison of Pressure-Drop For Two Slugs, 100% Quality Steam

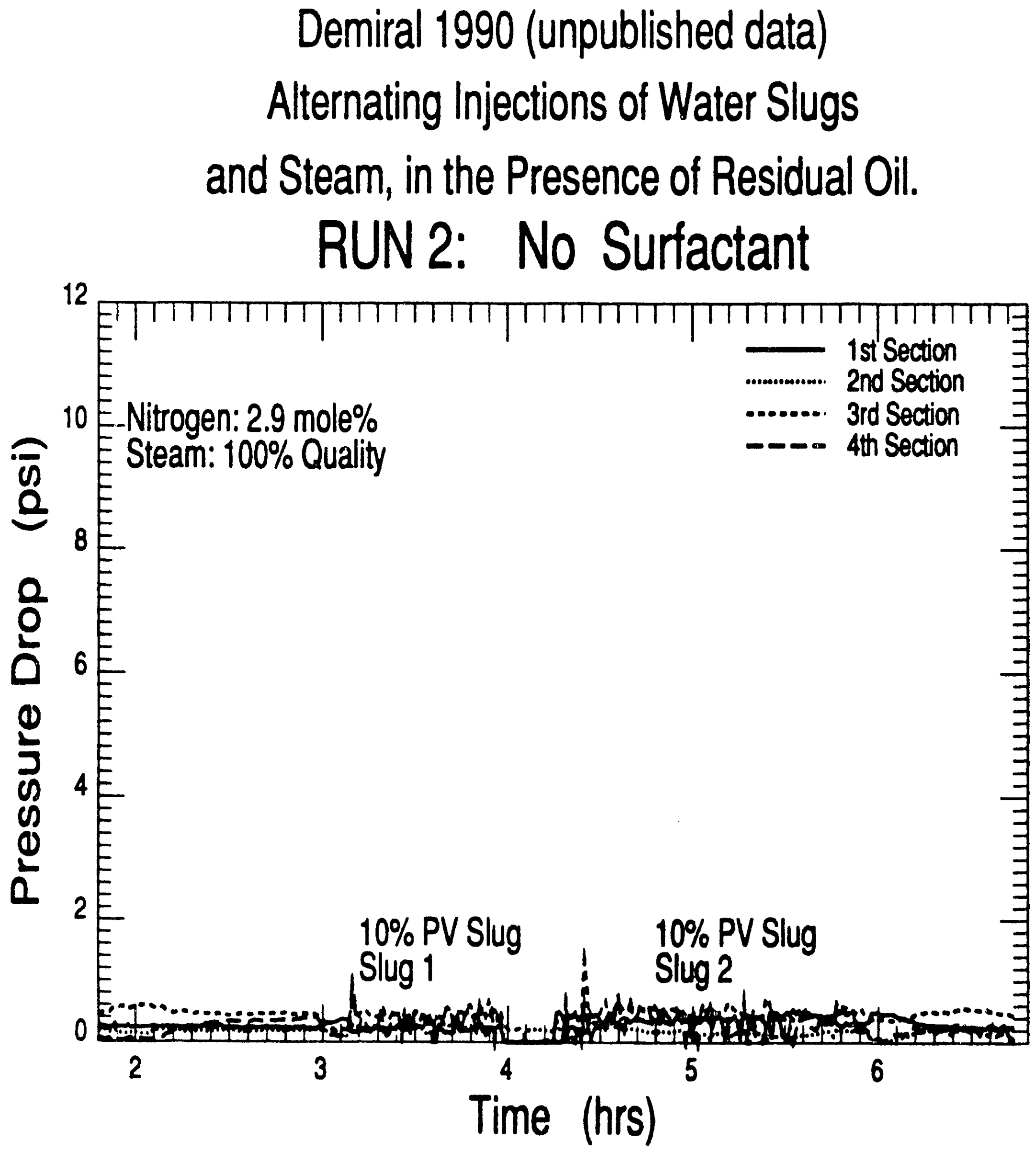
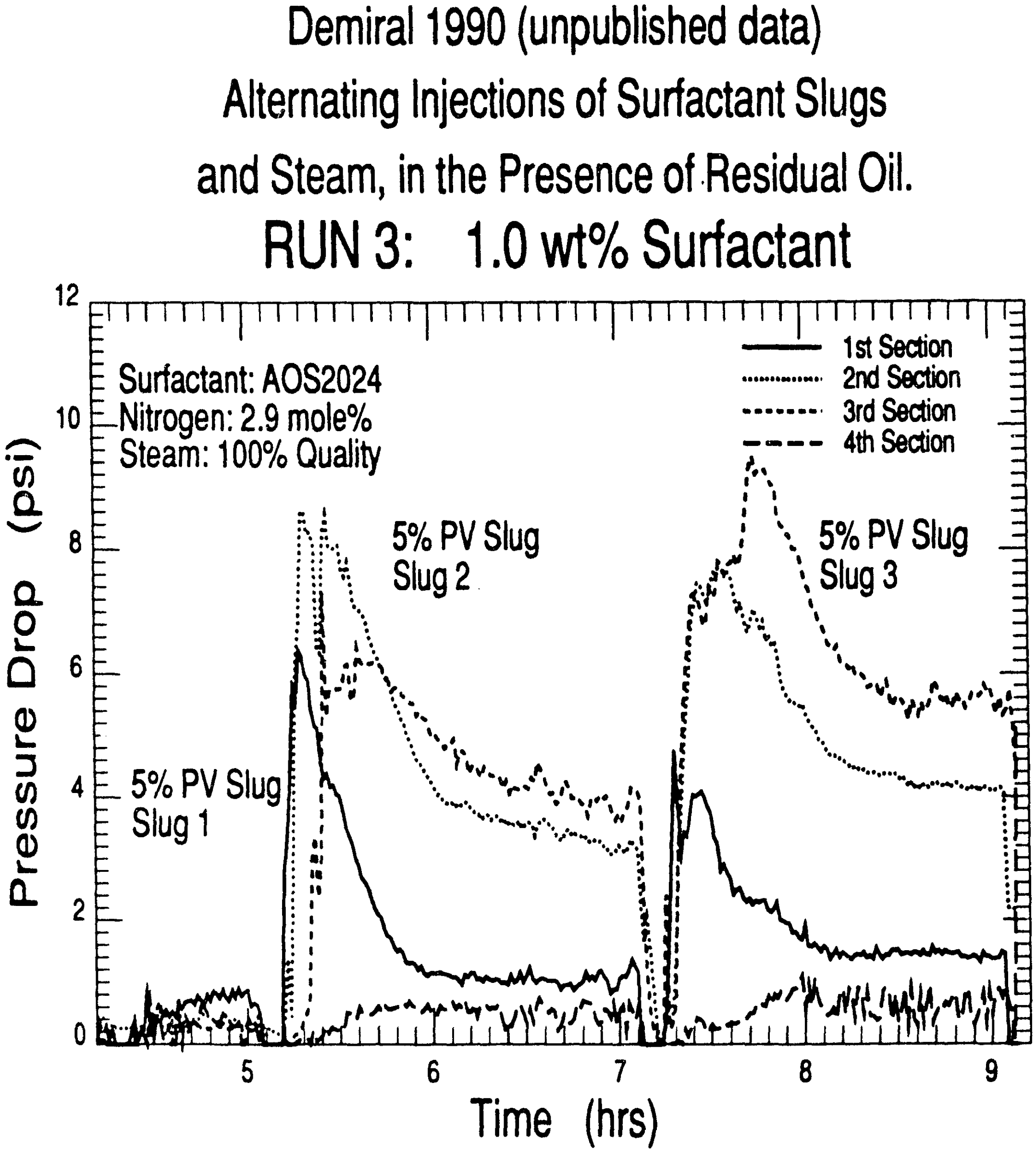


Figure 4.4: RUN 2: Pressure-Drop Across the Sandpack, 100% Quality Steam



Demiral 1990 (unpublished data)
Alternating Injections of Surfactant Slugs
and Steam, in the Presence of Residual Oil.
RUN 3: 1.0 wt% Surfactant

Figure 4.5: RUN 3: Pressure-Drop Across the Sandpack, 100% Quality Steam

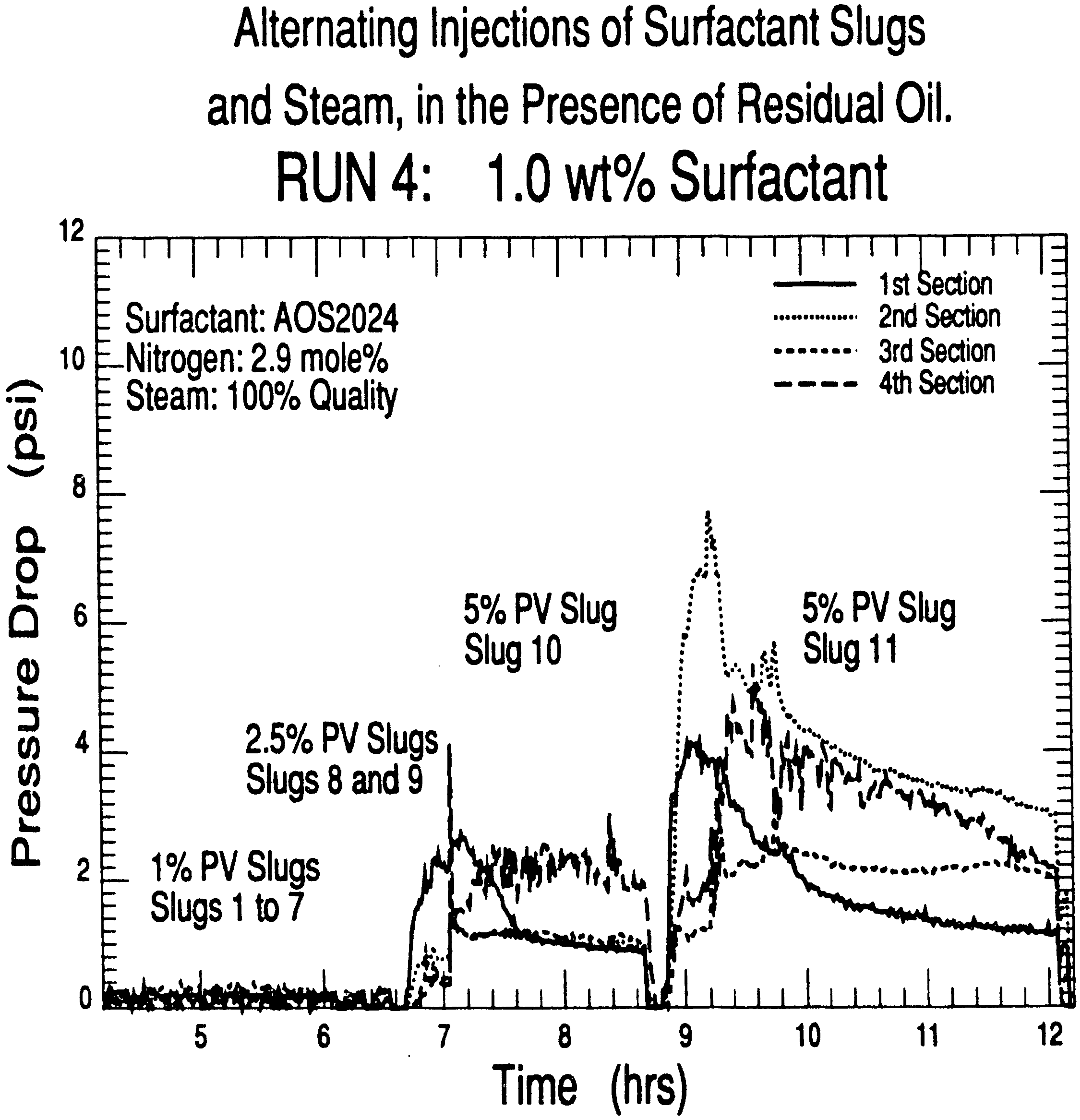


Figure 4.6: RUN 4: Pressure-Drop Across the Sandpack, 100% Quality Steam

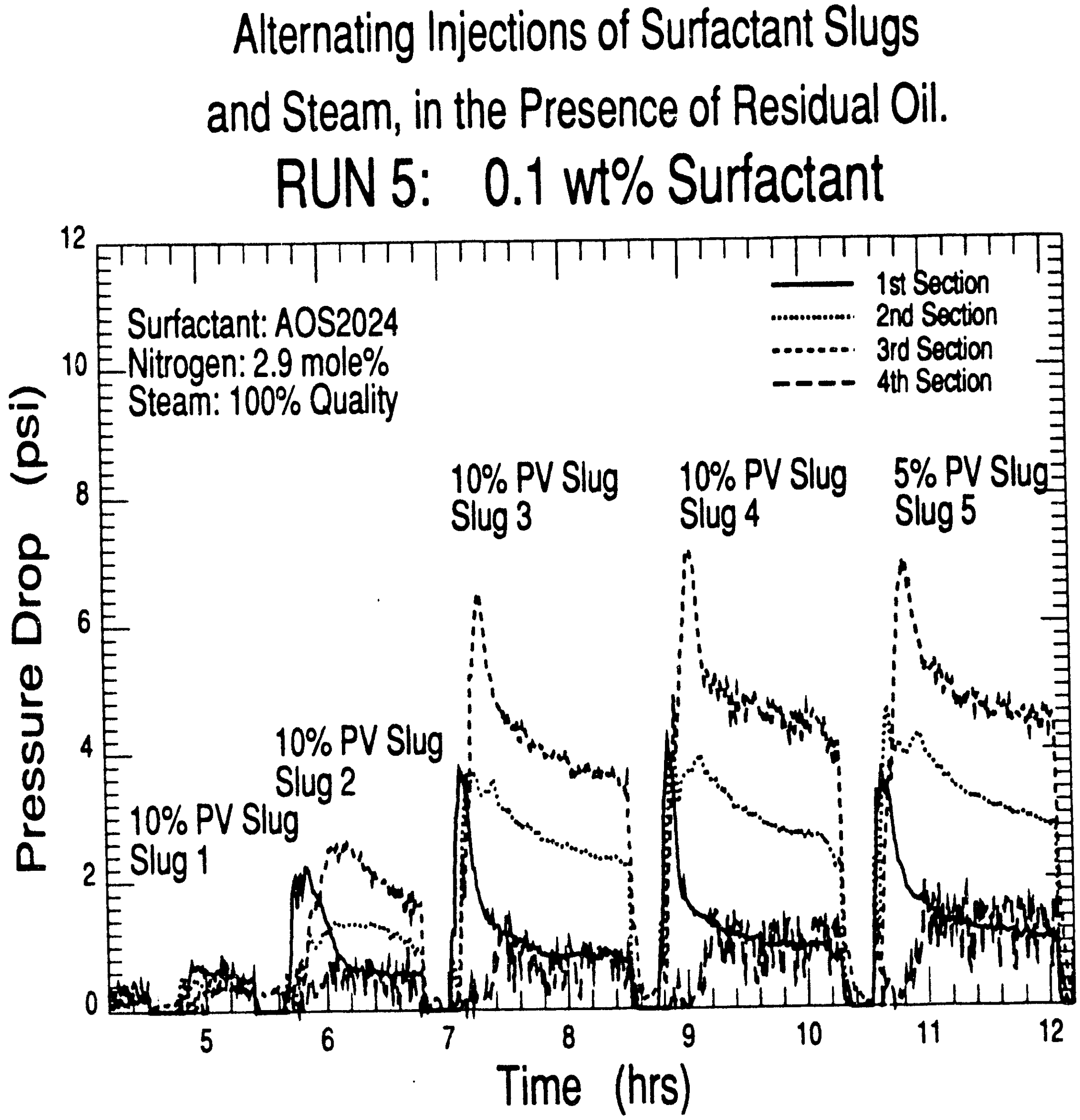


Figure 4.7: RUN 5: Pressure-Drop Across the Sandpack, 100% Quality Steam, Slugs 1 to 5

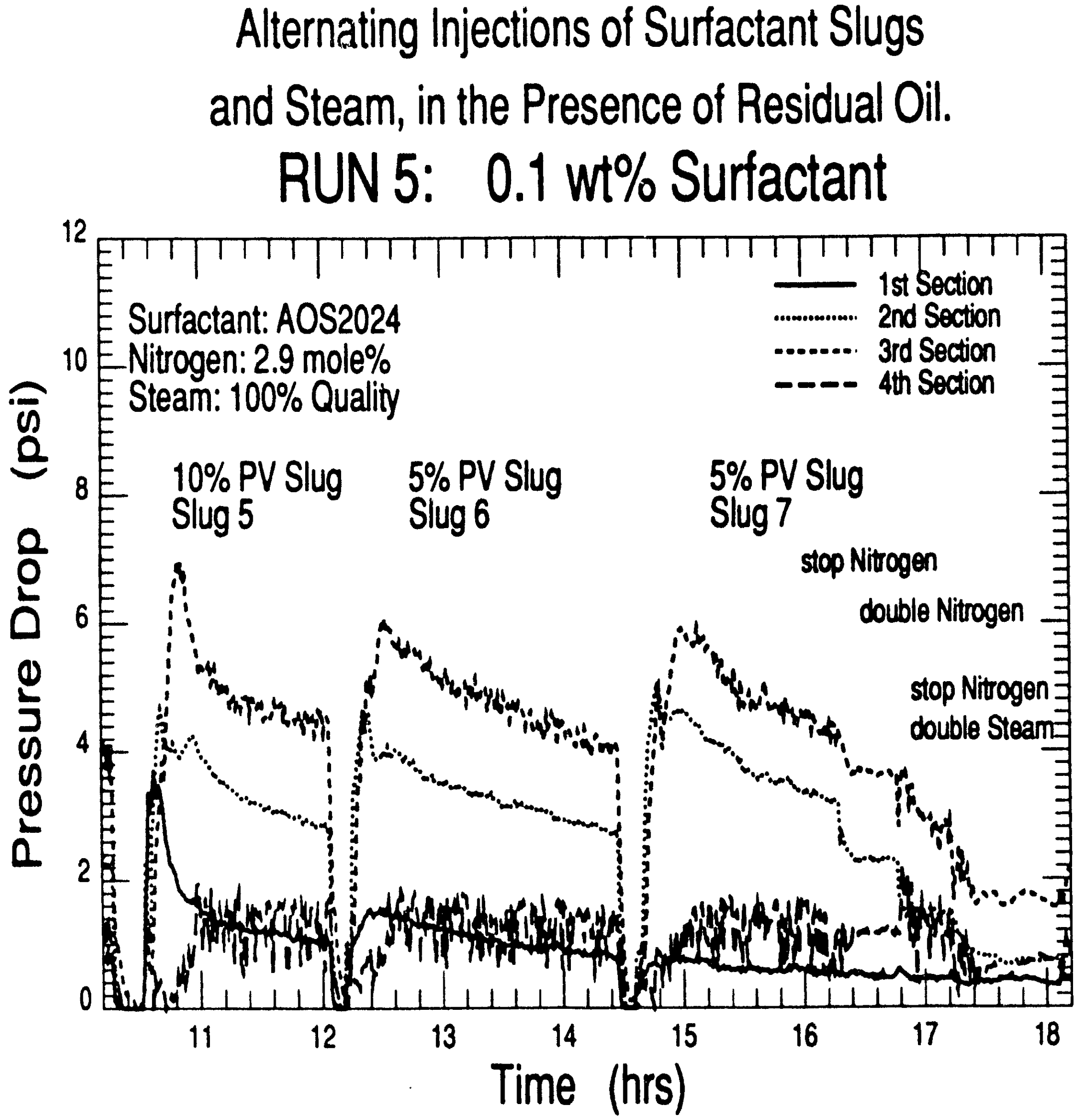


Figure 4.8: RUN 5: Pressure-Drop Across the Sandpack, 100% Quality Steam, Slugs 5 to 7

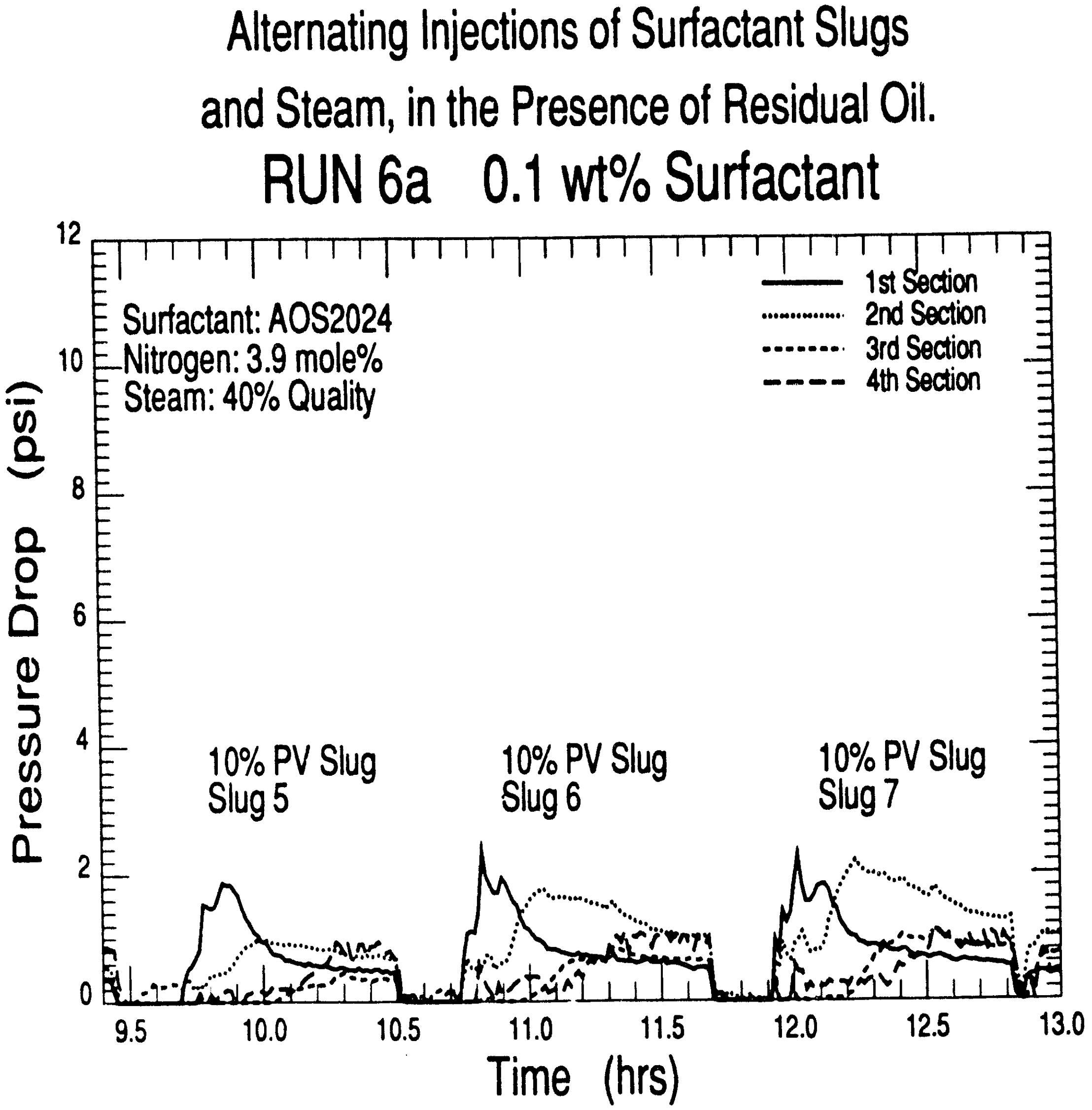


Figure 4.9: RUN 6a: Pressure-Drop Across the Sandpack, 40% Quality Steam, Slugs 5 to 7

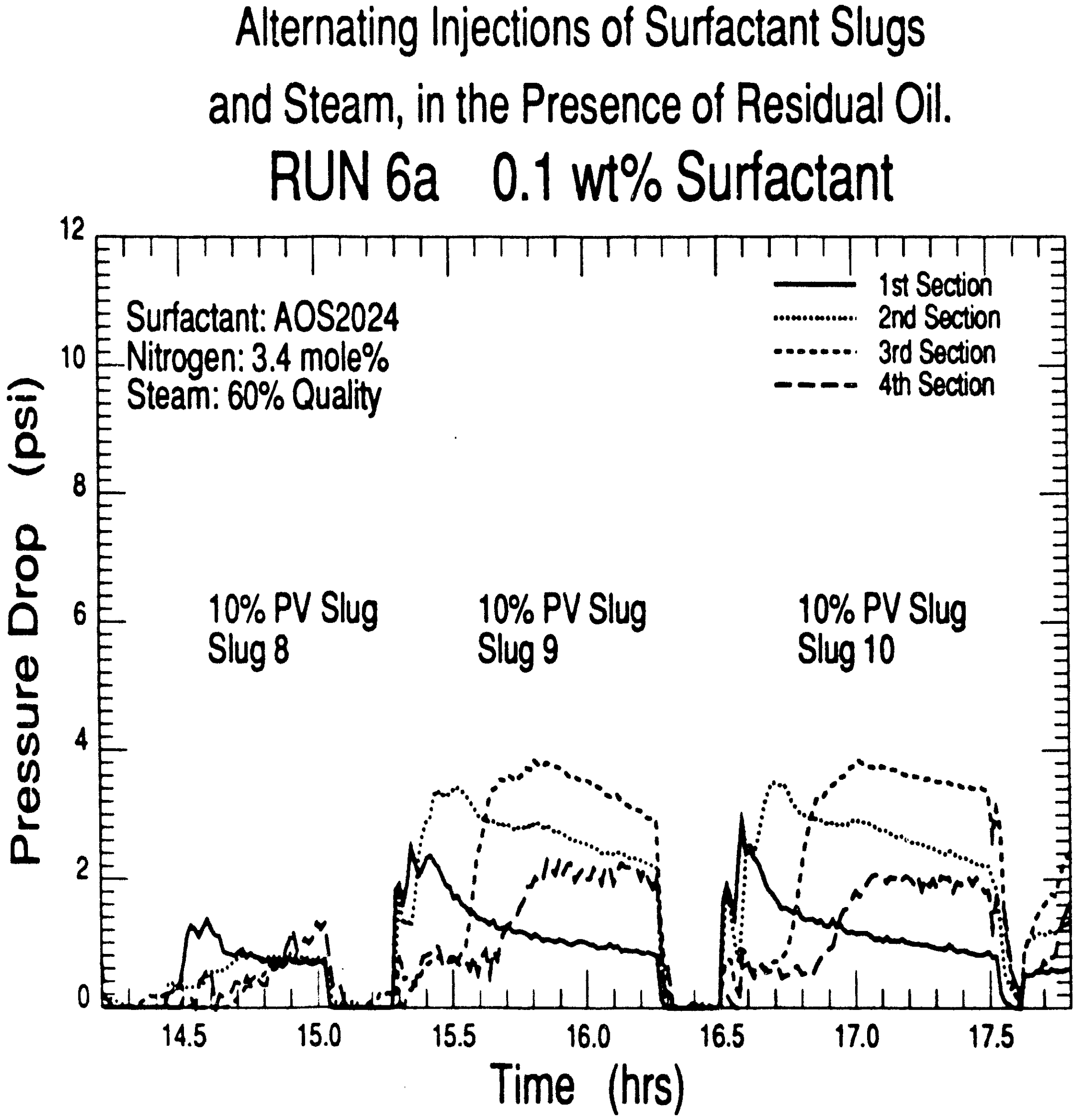


Figure 4.10: RUN 6a: Pressure-Drop Across the Sandpack, 60% Quality Steam, Slugs 8 to 10

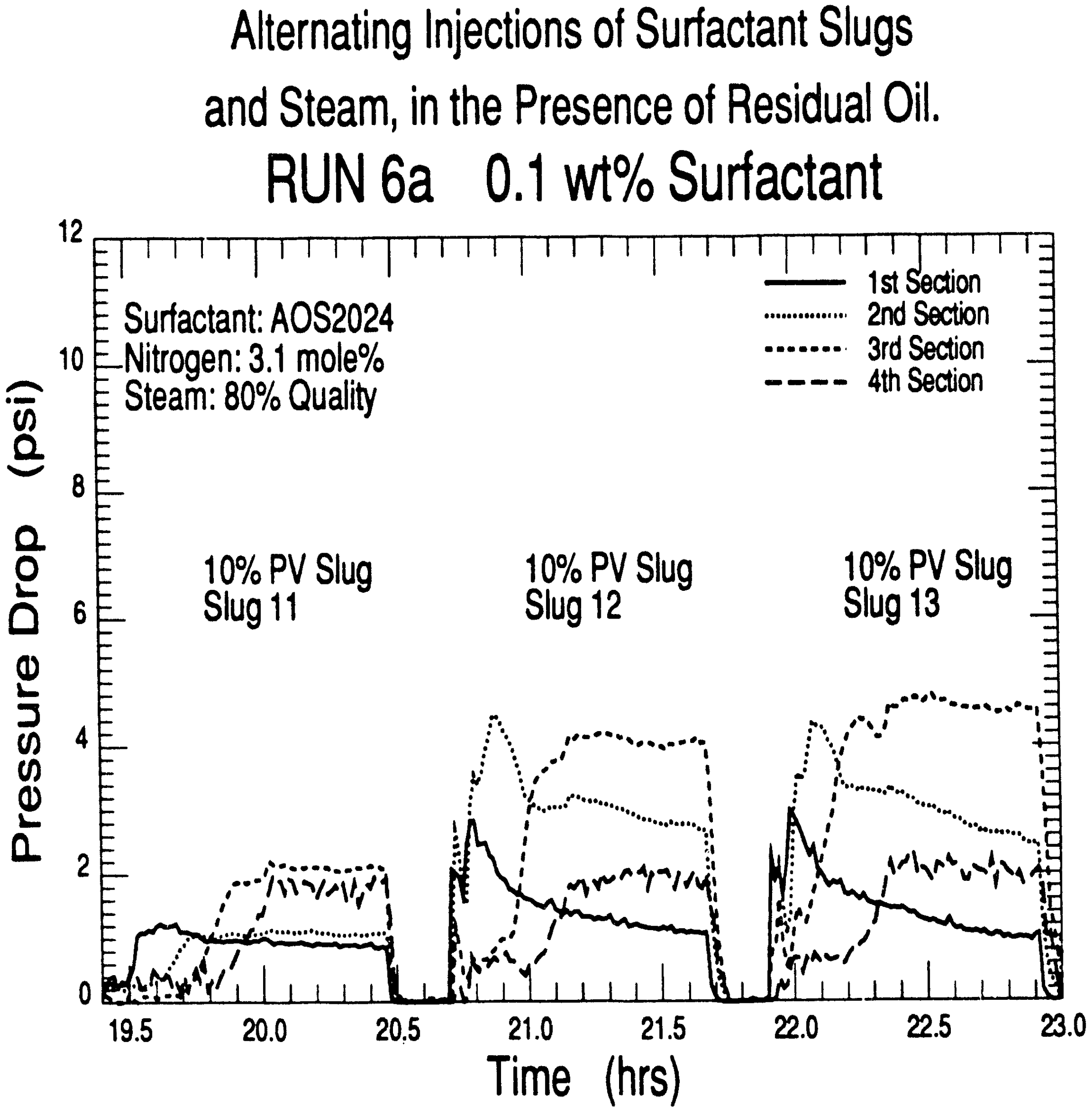


Figure 4.11: RUN 6a: Pressure-Drop Across the Sandpack, 80% Quality Steam, Slugs 11 to 13

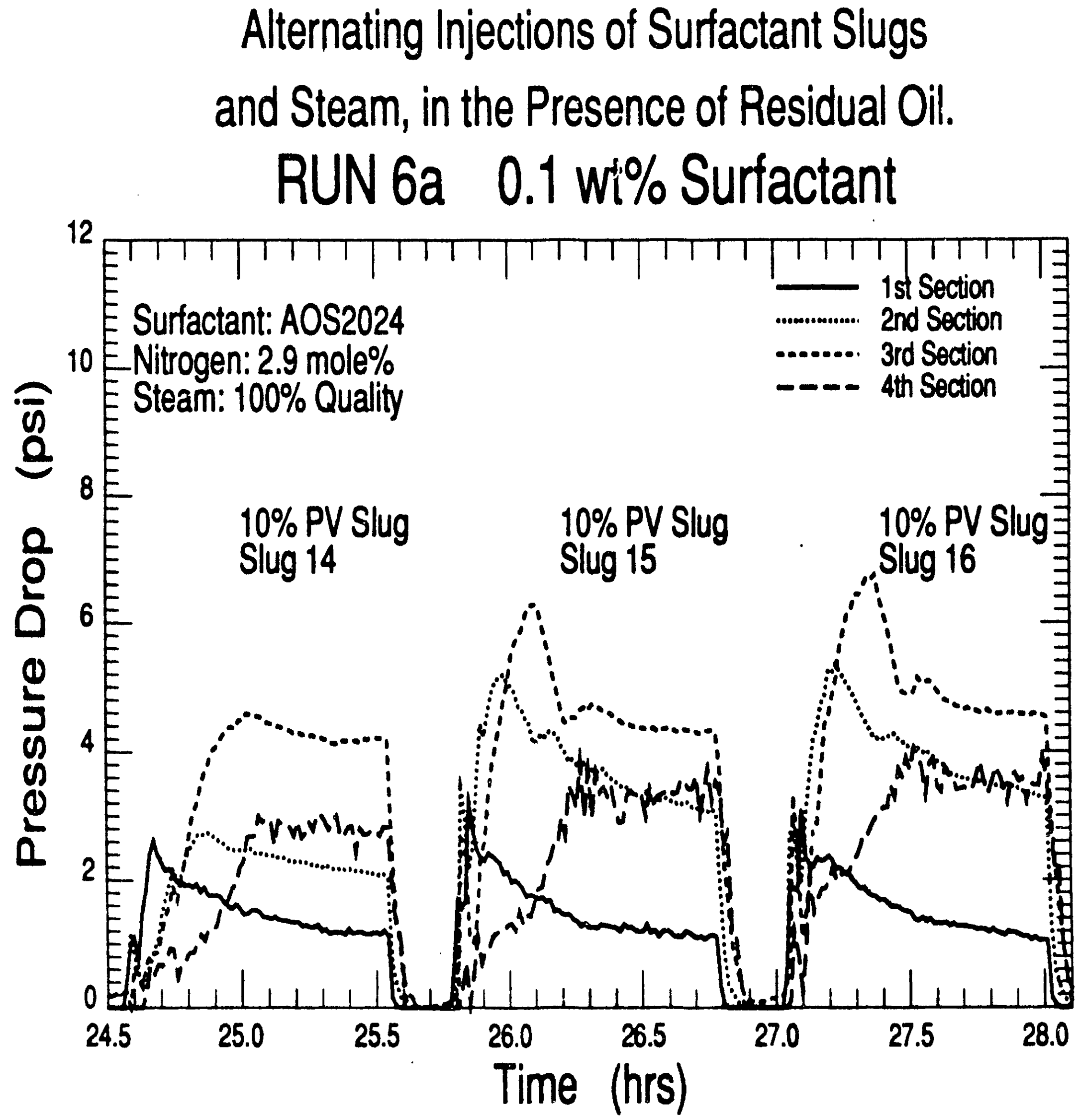
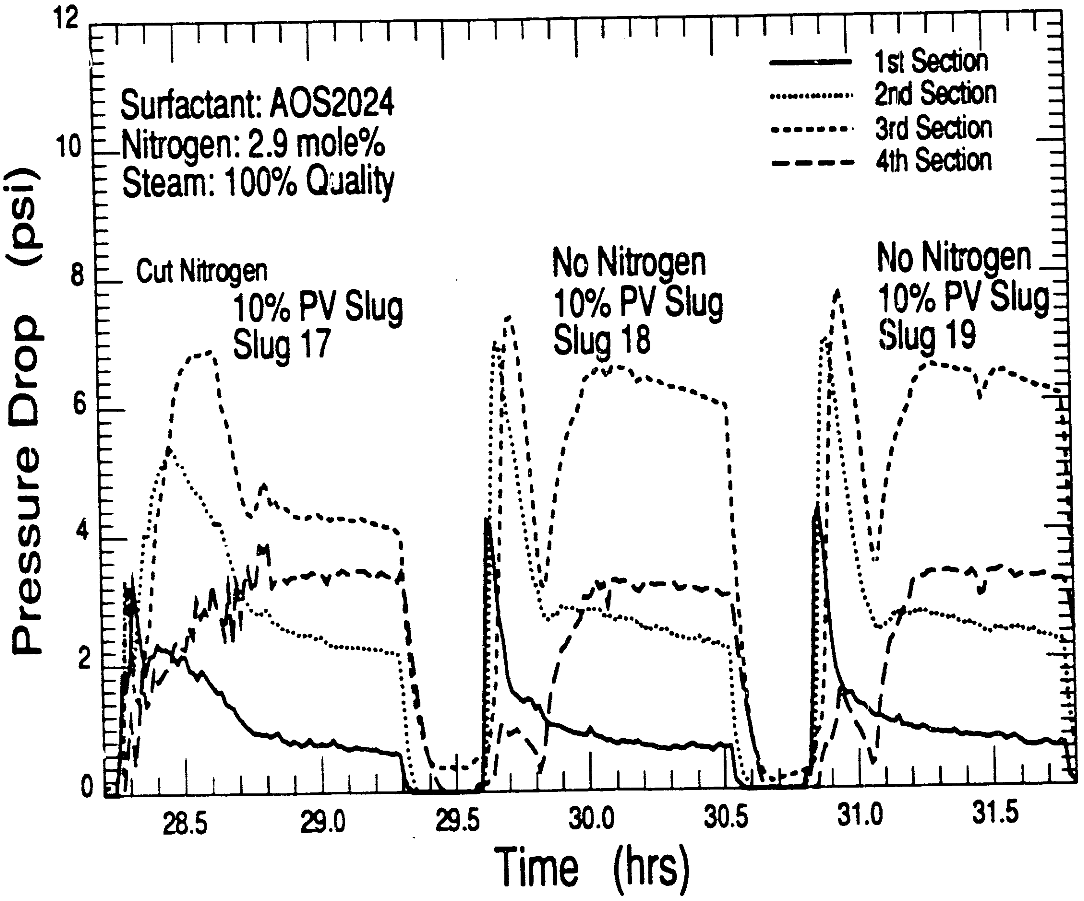


Figure 4.12: RUN 6a: Pressure-Drop Across the Sandpack, 100% Quality Steam, Slugs 14 to 16



Alternating Injections of Surfactant Slugs
and Steam, in the Presence of Residual Oil.
RUN 6a 0.1 wt% Surfactant

Figure 4.13: RUN 6a: Pressure-Drop Across the Sandpack, 100% Quality Steam, Slugs 17 to 19

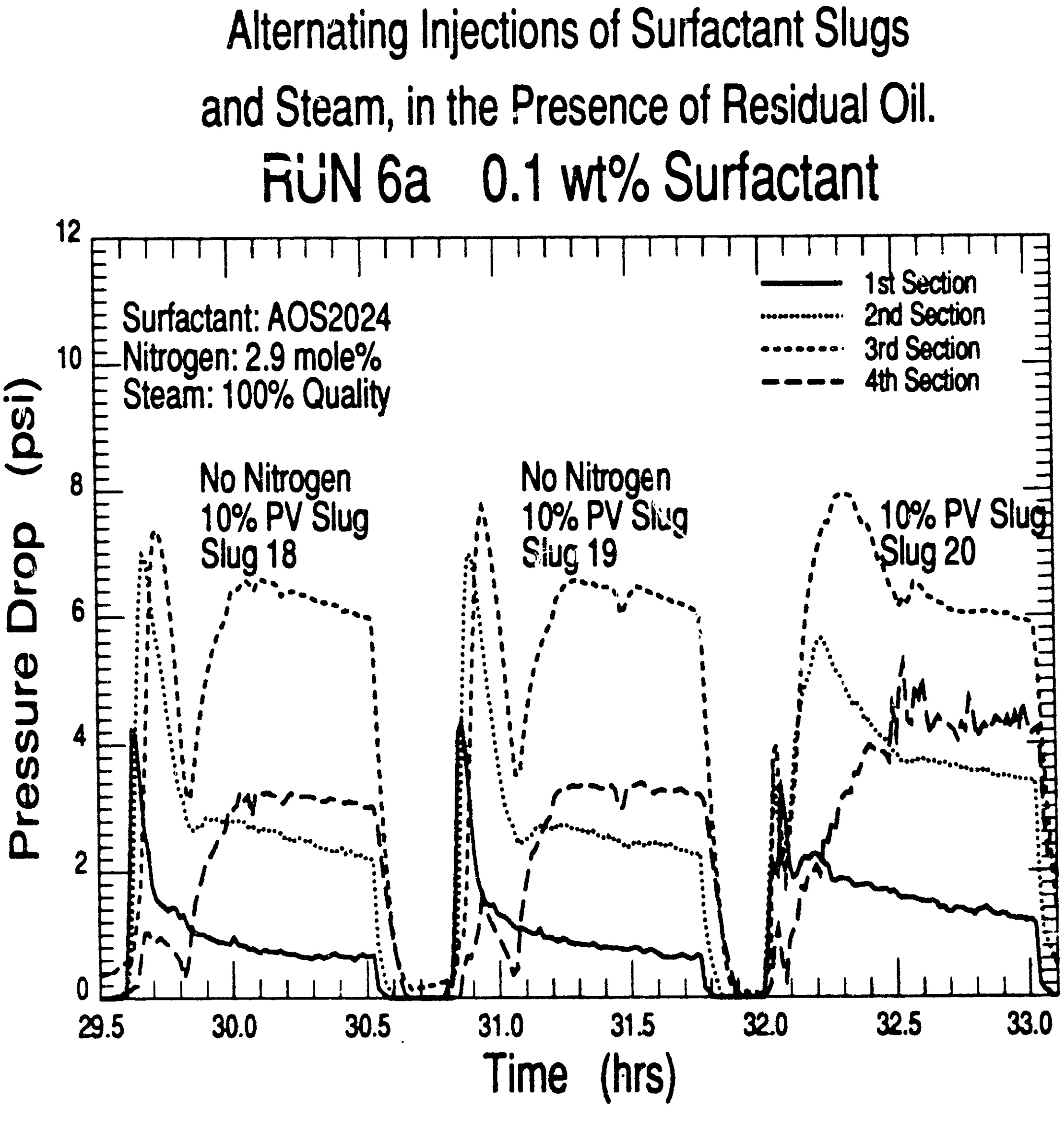


Figure 4.14: RUN 6a: Pressure-Drop Across the Sandpack, 100% Quality Steam, Slugs 18 to 20

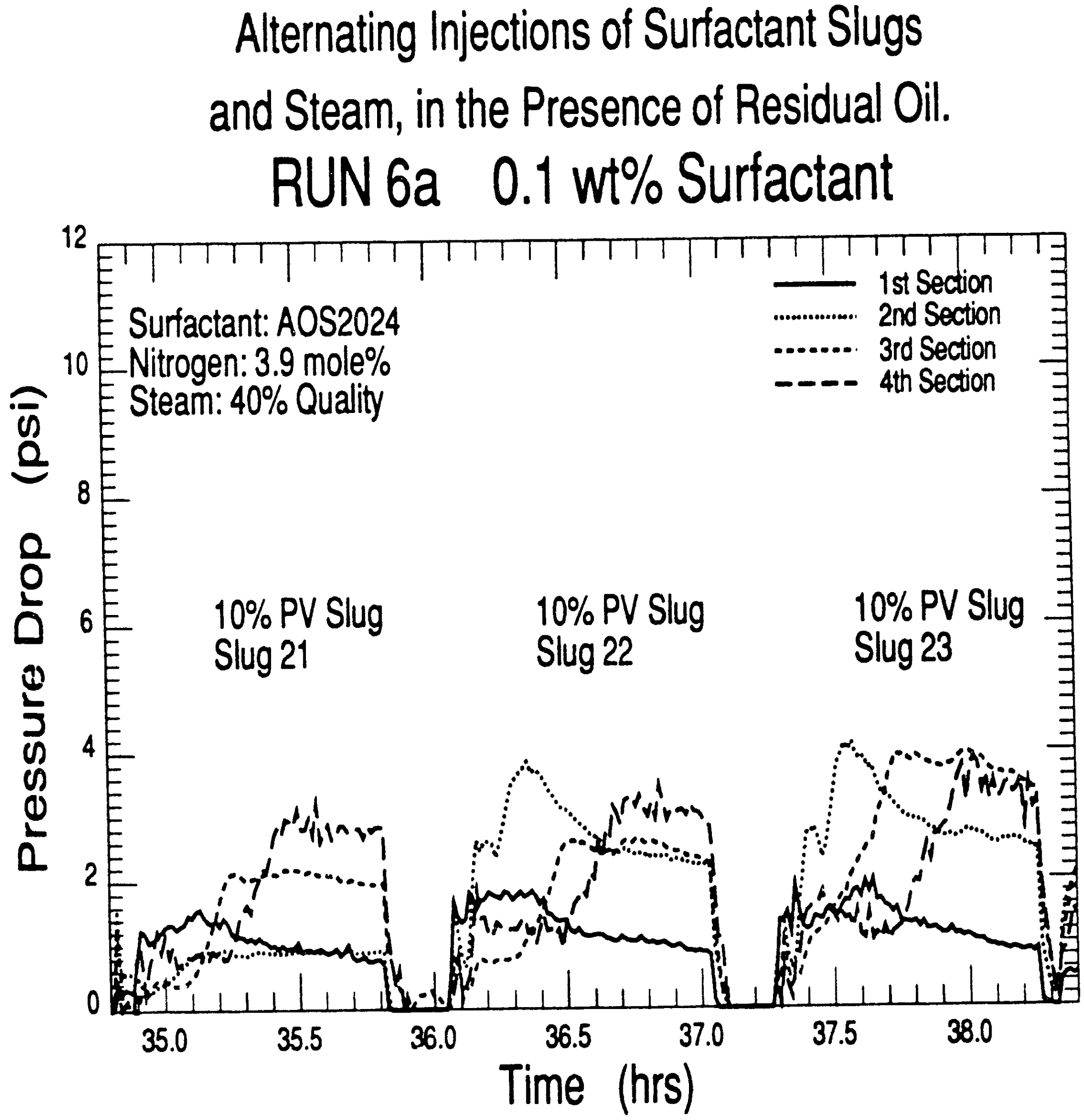
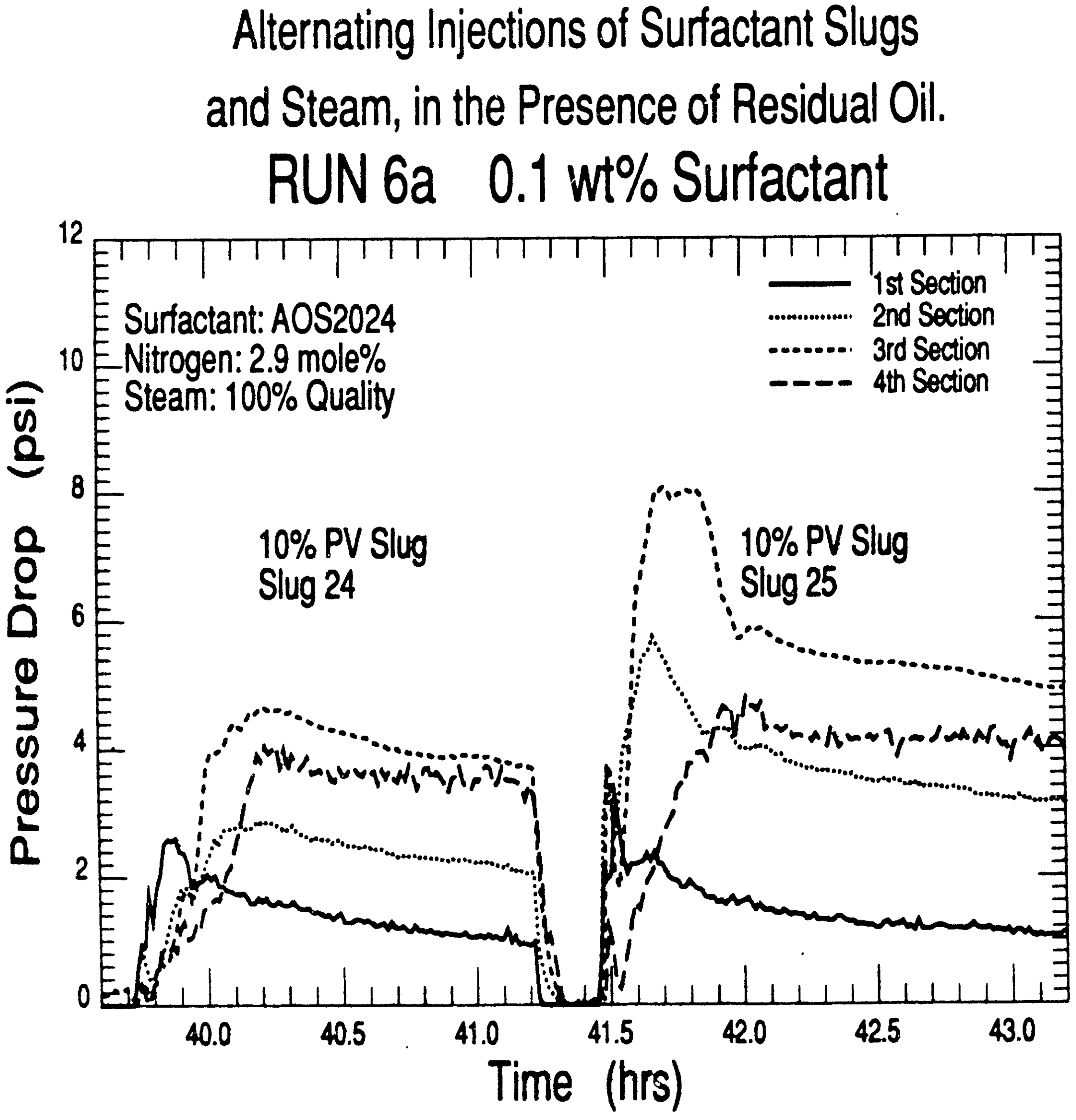


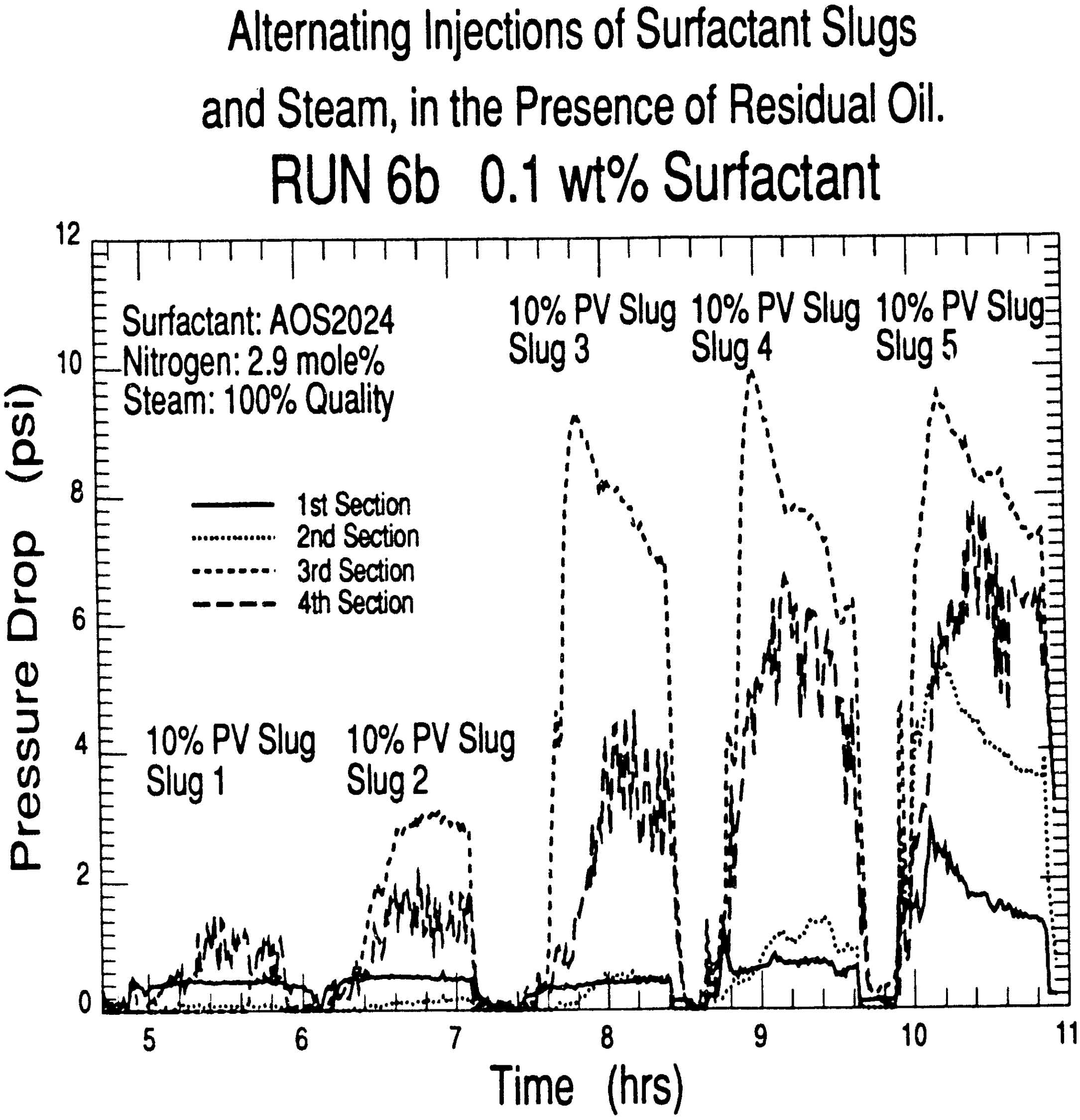
Figure 4.15: RUN 6a: Pressure-Drop Across the Sandpack, 40% Quality Steam, Slugs 21 to 23



Alternating Injections of Surfactant Slugs and Steam, in the Presence of Residual Oil.

RUN 6a 0.1 wt% Surfactant

Figure 4.16: RUN 6a: Pressure-Drop Across the Sandpack, 100% Quality Steam, Slugs 24 and 25



Alternating Injections of Surfactant Slugs and Steam, in the Presence of Residual Oil.

RUN 6b 0.1 wt% Surfactant

Figure 4.17: RUN 6b: Pressure-Drop Across the Sandpack, 100% Quality Steam

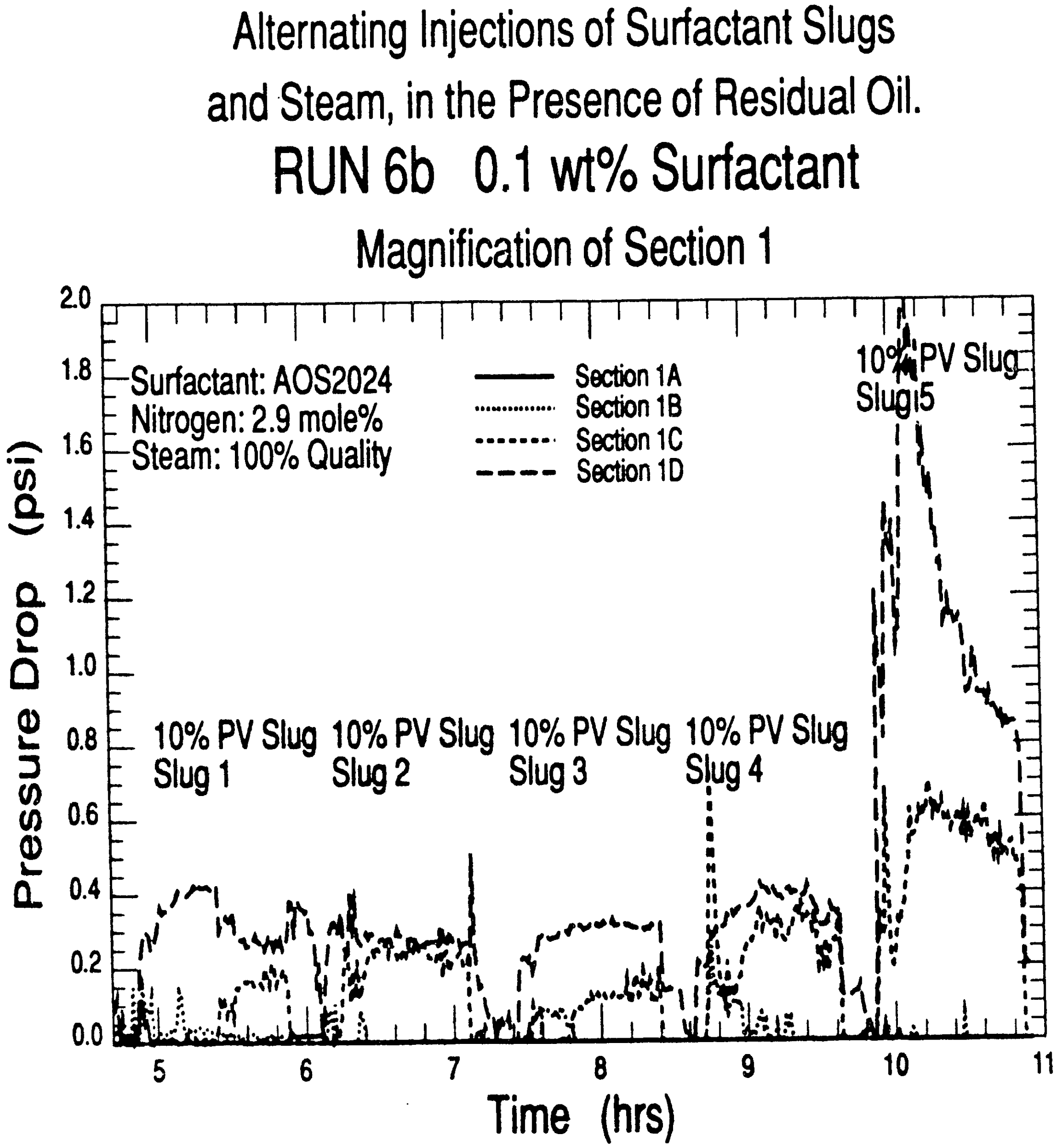


Figure 4.18: RUN 6b: Pressure-Drop Across the Sandpack, 100% Quality Steam, Section 1

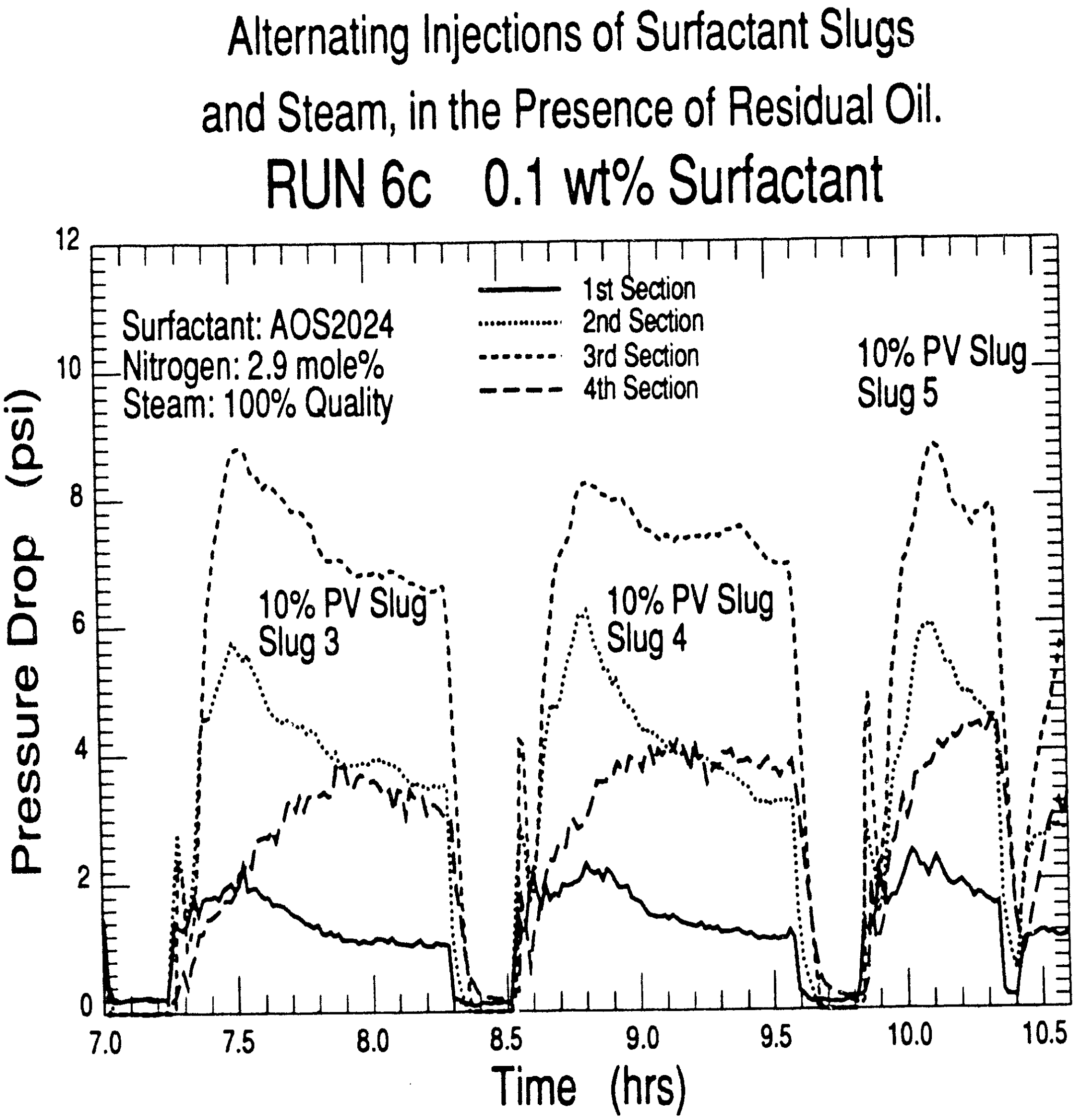


Figure 4.19: RUN 6c: Pressure-Drop Across the Sandpack, 100% Quality Steam, Slugs 3 to 5

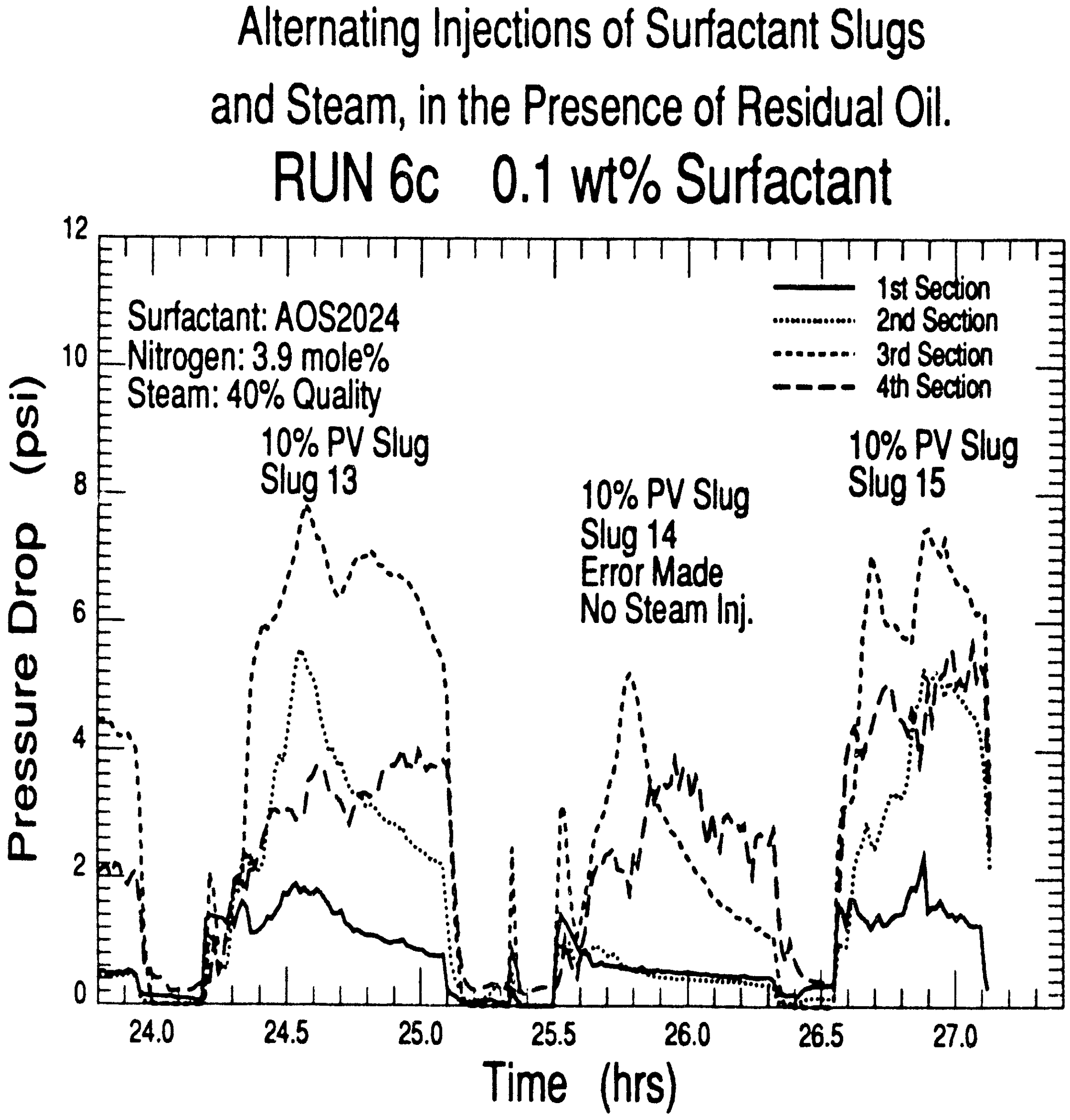
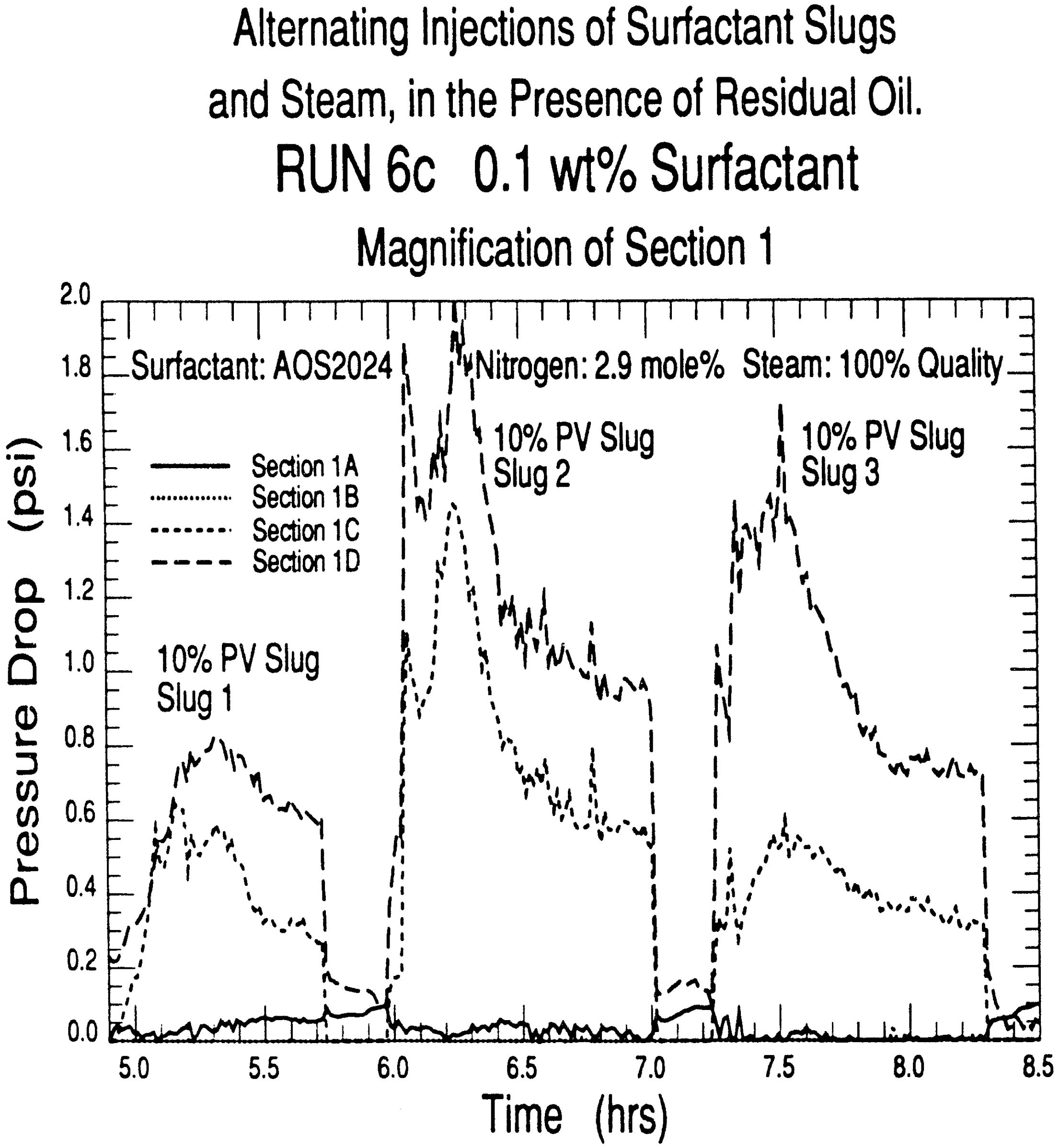


Figure 4.20: RUN 6c: Pressure-Drop Across the Sandpack, 40% Quality Steam, Slugs 13 to 15



Alternating Injections of Surfactant Slugs and Steam, in the Presence of Residual Oil.

RUN 6c 0.1 wt% Surfactant

Magnification of Section 1

Figure 4.21: RUN 6c: Pressure-Drop Across the Sandpack, 100% Quality Steam, Section 1, Slugs 1 to 3

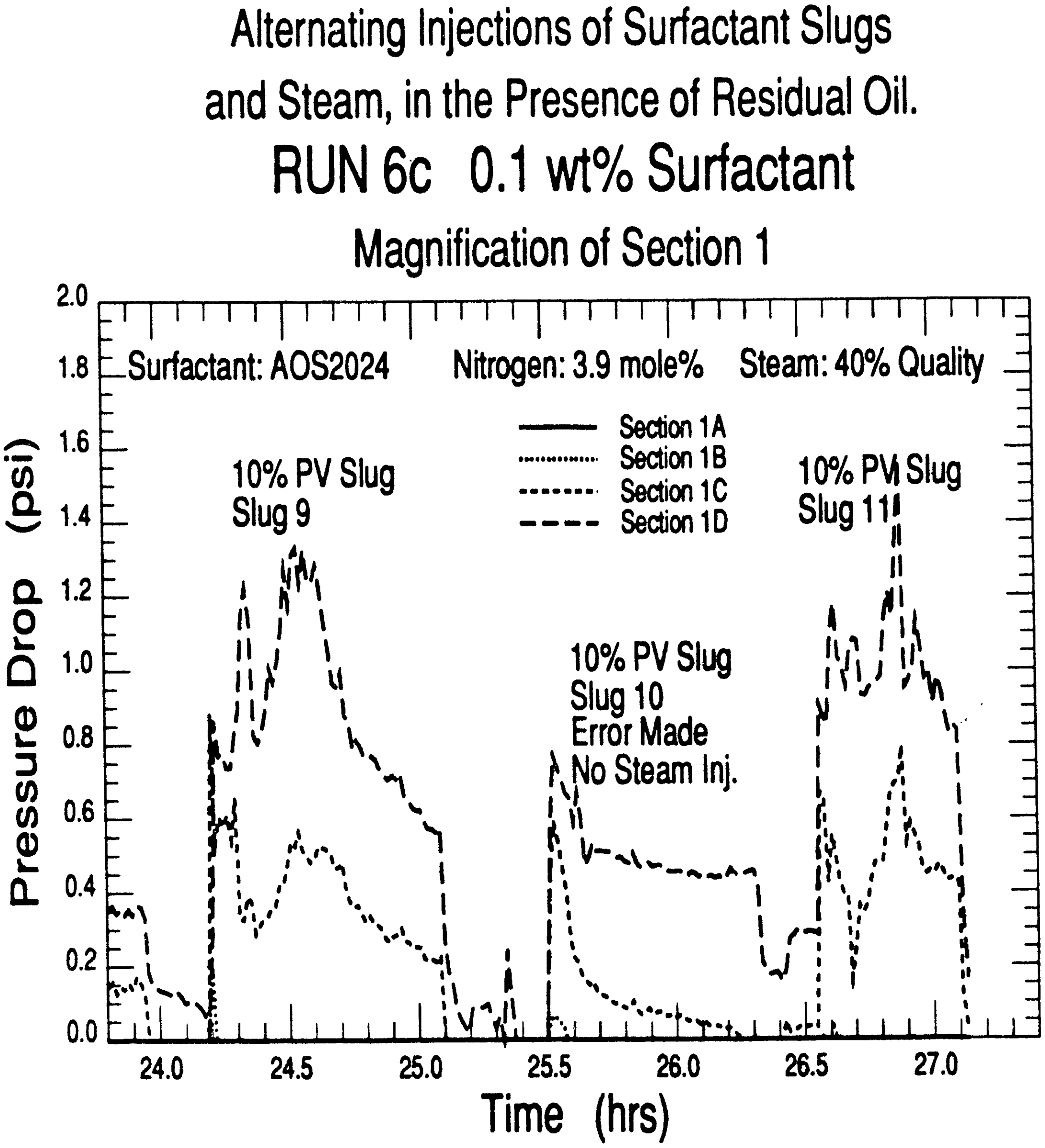


Figure 4.22: RUN 6c: Pressure-Drop Across the Sandpack, 40% Quality Steam, Section 1, Slugs 9 to 11

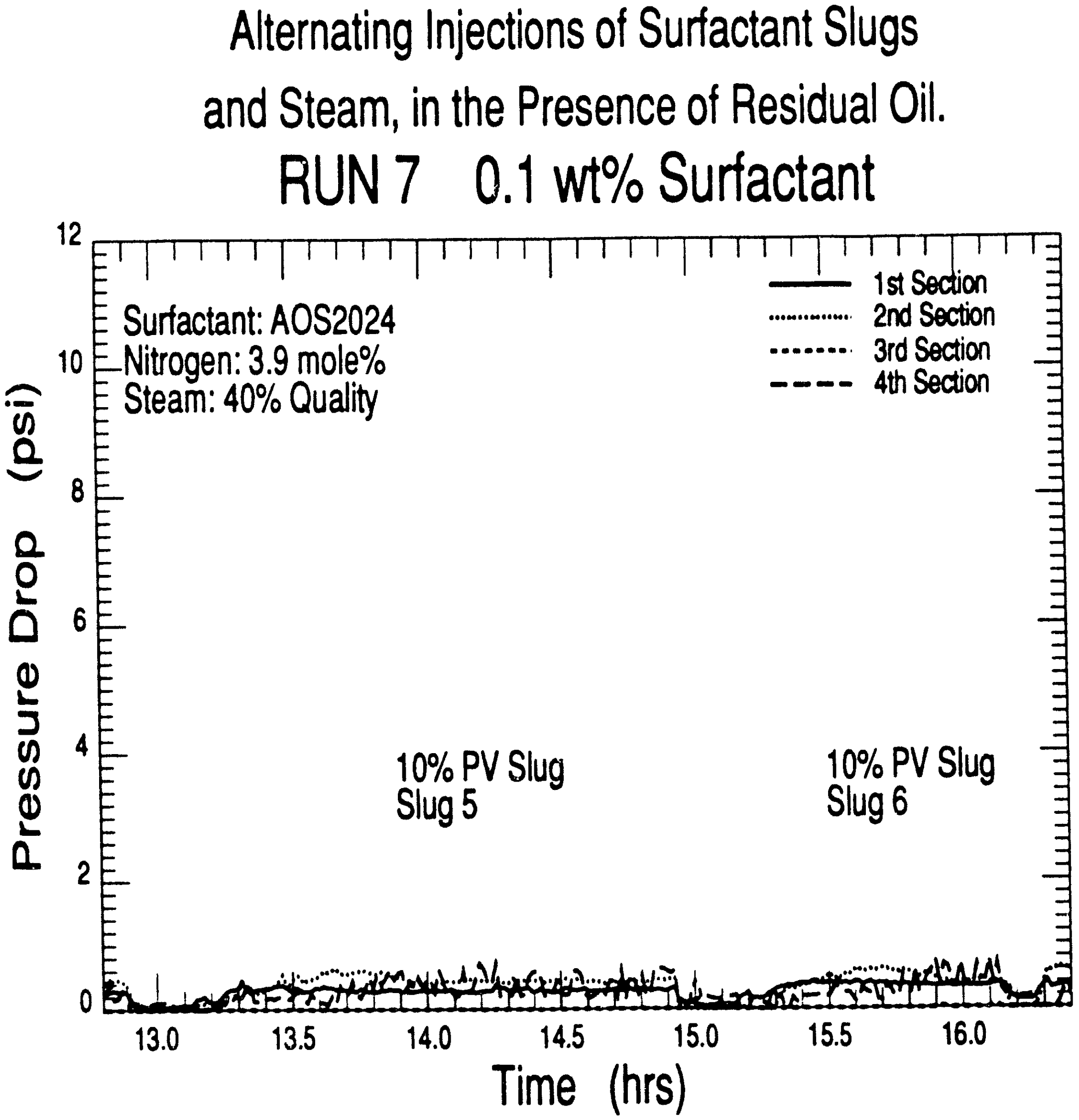


Figure 4.23: RUN 7: Pressure-Drop Across the Sandpack, 40% Quality Steam, Slugs 5 and 6

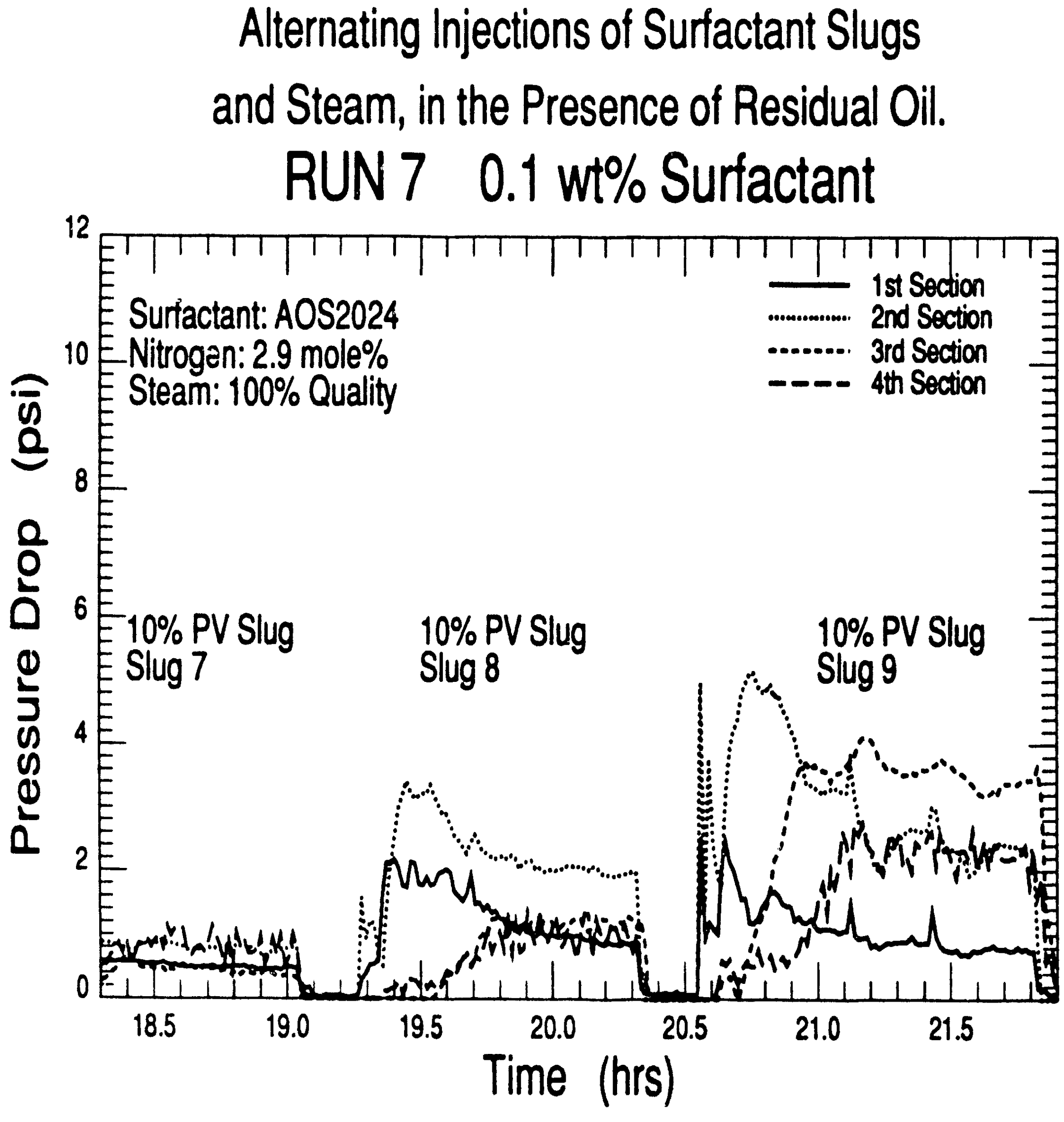


Figure 4.24: RUN 7: Pressure-Drop Across the Sandpack, 100% Quality Steam, Slugs 7 to 9

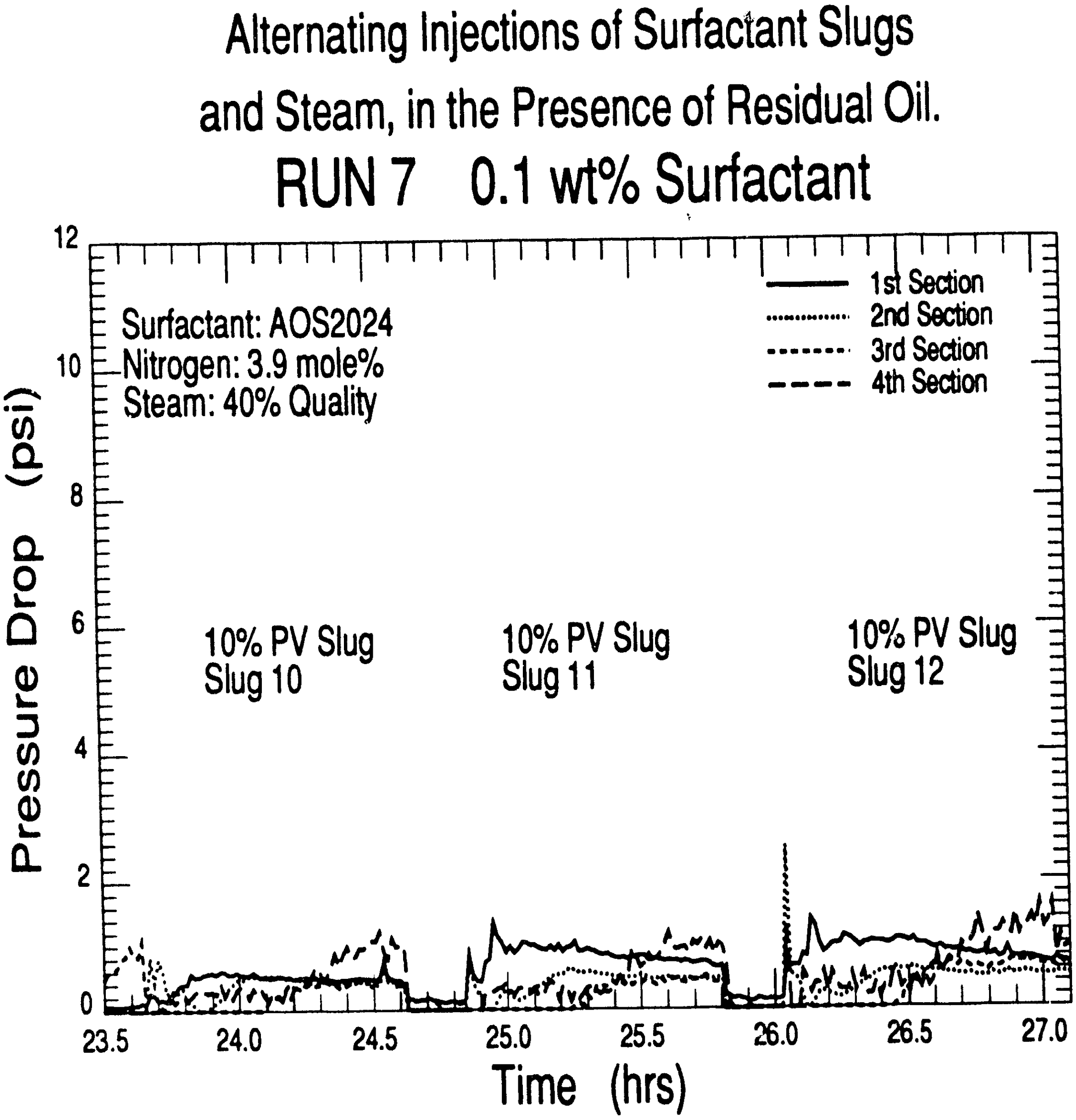


Figure 4.25: RUN 7: Pressure-Drop Across the Sandpack, 40% Quality Steam, Slugs 10 to 12

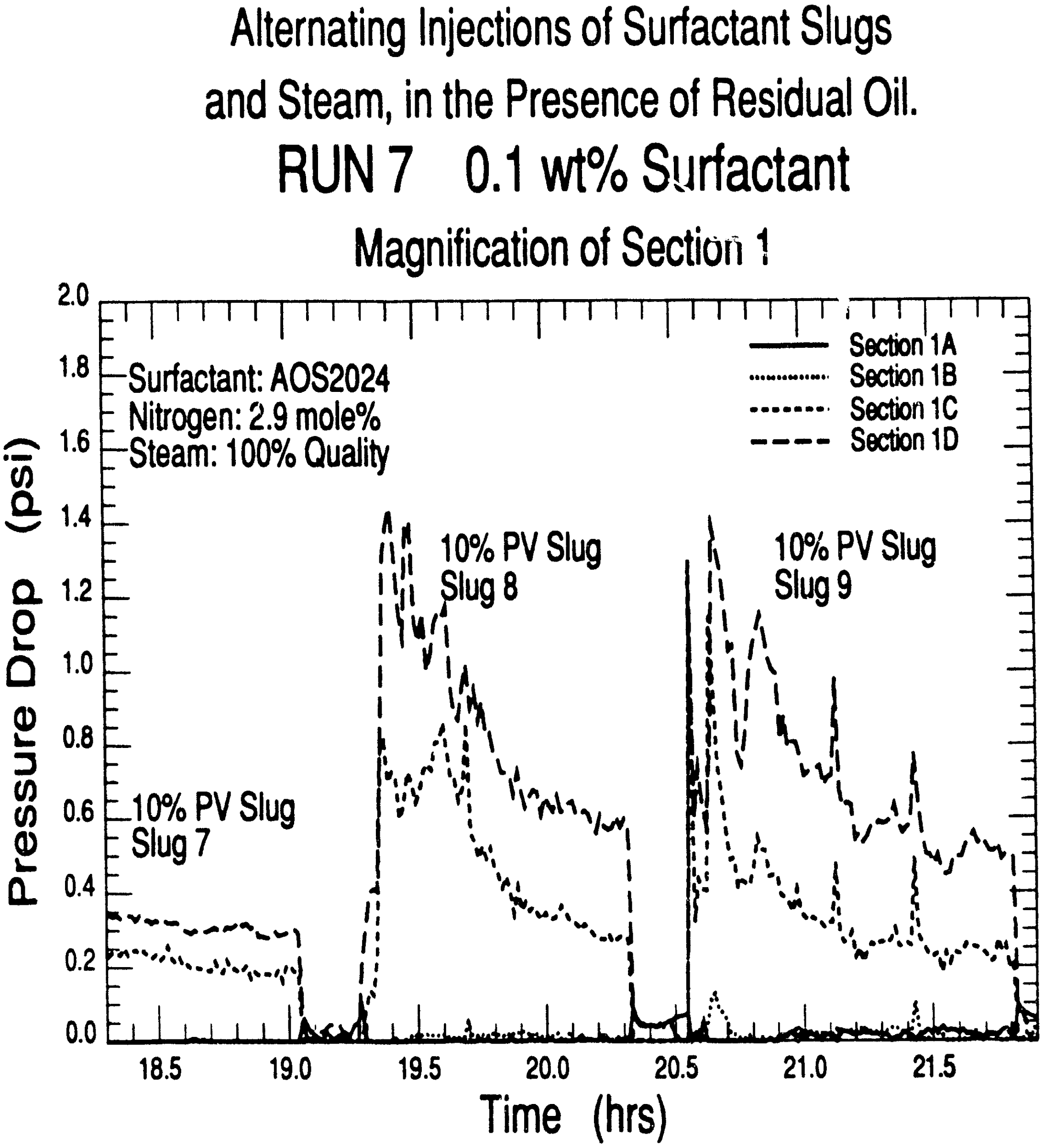


Figure 4.26: RUN 7: Pressure-Drop Across the Sandpack, 100% Quality Steam, Section 1, Slugs 7 to 9

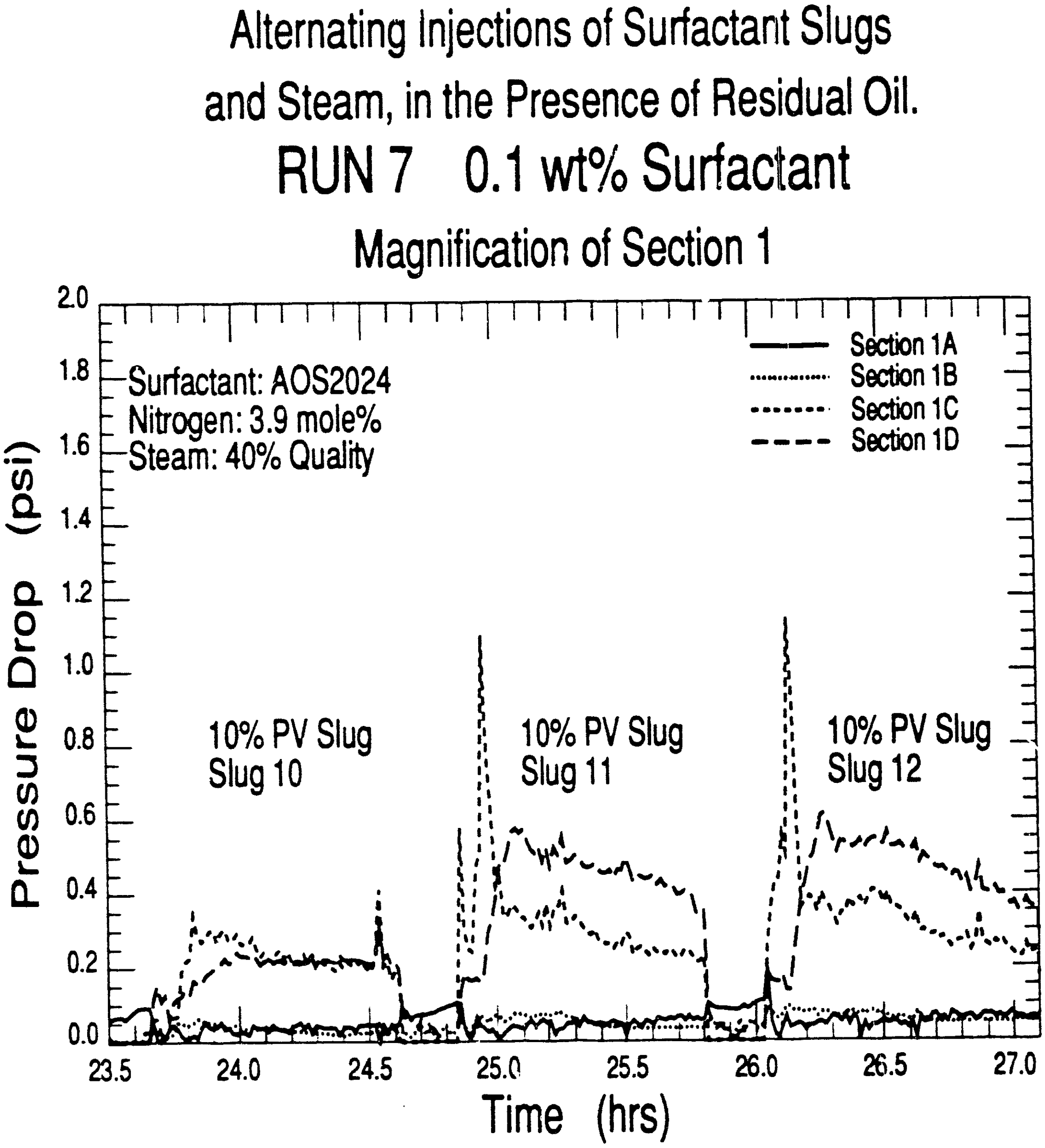


Figure 4.27: RUN 7: Pressure-Drop Across the Sandpack, 40% Quality Steam, Section 1, Slugs 10 to 12

5. Conclusions

Under our experimental conditions, the following conclusions are drawn:

1. A steam foam flood can have significantly different results depending upon whether the surfactant is coinjected with steam (SIS) or batched ahead of the steam (SAG), with SAG proving superior to SIS. The advantage of SAG over SIS may result from increased mixing between phases since SAG forces steam to constantly reestablish a path through the surfactant rich aqueous phase after each slug injection.

2. Adsorption and partitioning of surfactant from the first few slugs of a SAG procedure can greatly reduce similar losses from subsequent slugs.

3. SAG performance is improved when using high quality steam. The disadvantage of employing low quality steam may be that surfactant adsorbed and partitioned from early slugs is constantly washed away by the clean water of low quality steam. The result is that subsequent slug injections must continuously replentish adsorption sites and repartition into the oil phase, with the result that less is available to stabilize foam. It is felt that a large amount of surfactant resides at oil-water interfaces where the hydrophobic tail and hydrophilic head are preferentially stable, i.e. adsorbed onto the oil surface, with actual partitioning into the oil interior being minor. One possible problem is that the drying ability of high quality steam may cause wettability alterations and reduced foam stability near an injector. From a practical standpoint, however, selectively eliminating foam generation directly beside an injector can advantageous raise injectivity, resulting in higher velocities and engendering foam formation deeper within the reservoir.

4. The success of SAG requires that slug sizes be above a minimum that can ensure good mixing and sufficient wetting phase. Above this minimum a dilute slug can prove almost as effective as a concentrated one (0.1 vs 1.0 wt%), indicating that significant savings in surfactant usage is possible.

5. SAG increases steam and nitrogen resistance significantly more than water alternating gas (WAG).

6. Low residual oil saturations of about 12% greatly destabilize foam (AOS2024) in-situ.

6. Recommendations

The experimental conditions can be broadened by several different paths. Some options which could be the topic of future Master's reports are suggested below:

1. Repeat all the runs using a different conventional surfactant type to verify the general explanations offered in this report.
2. Repeat Runs 1, 2, and 3 with several different conventional surfactant types (i.e., LTS, LXS, IOS), again, to verify the general observations made in this report. A nonconventional 'oil resistant' type could also be tried.
3. Use a heterogeneous sandpack to compare SIS vs SAG. The additional mixing resulting from the heterogeneity may be sufficient for foam generation using SIS and to reduce the minimum slug size found with SAG. The mixing concept could also be explored by increasing steam and surfactant flowrates in the SIS procedure.
4. Perform micromodel experiments to visually record the transition from MAB to BTT flow and thereby verify the concept of Tranport Modes. The experiments could also determine if the onset of MAB is synonymous with the break point observed by various researchers. For this determination the recording of pressure drop across the model is essential.

   For a model of constant permeability, the variables are surfactant concentration and foam quality. A suggested procedure would begin with a surfactant solution saturated (0.5 wt%) micromodel and low injected foam quality (50%). If the observed flow is not by BTT then either a lower quality or higher concentration is necessary. Assuming BTT is observed then the injected quality could be increased at increments of 5 to 10 percent, carefully allowing time for system stabilization to occur. At a sufficiently high foam quality the foam flow mode should change to MAB.
5. Employ a SAG procedure with steam and a 50:50 mixture of nonconventional and conventional (NCC) surfactant in a 3-D model containing heavy oil. Compare oil recovery and sweep efficiency vs time with that obtained using conventional surfactant only and with that obtained using WAG. The differences should be substantial as the NCC mix will lower steam mobility in the oil sections, yet lower steam mobility even further in the steam swept sections. The exact NCC mixture would need to be optimized.
6. Compare the pressure drop using the standard SAG procedure used in this report with a SAG procedure that utilizes the 'surfactant soak' concept, whereby the surfactant slug is allowed to soak for some time before resuming steam injection. The soak time would need to be optimized, but an initial soak of a few hours is suggested. The soak should result in a stronger response to the initial slugs and should also reduce the quality effects seen in this study. Soak times for subsequent slugs should be shortened or eliminated altogether as the limiting maximum pressure drop is reached.

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8. Appendix

8.1 Appendix A: Residual Oil Calculation

Table 8.1: Produced Fluids During Oil and Steam Flooding

Run	Produced Water During Oil Flooding (ml)	Produced Oil During Steam Flooding (ml)	Residual Oil $(Col2 - Col3)/PV$ $1PV = 1500ml$
1	1500	1300	0.133
2	1400	1240	0.107
3	1500	1240	0.173
4	1400	1200	0.133
5	1400	1260	0.093
6	1400	1200	0.133
7	1380	1290	0.060
mean			0.119

The mean is probably the best estimate for any given run since the residual oil calculations are extremely sensitive to the volumes used, which cannot be measured with high accuracy. This is especially true for the column 3 value since the produced water oil emulsions are not easily separated, even with addition of demulsifier. As an example, with only a 2.5% variation in columns 2 and 3, the ROS of RUN 7 would be 0.104, which is subtantially different than the 0.060 value calculated. Also, the values of 1500 ml in column 1 for RUNS 1 and 3 are questionable since the implication is that no residual water is left in the sandpack after oil flood.

8.2 Appendix B: Surfactant Analytical Data and Solution Preparation

Table 8.2: Surfactant Analytical Data

Surfactant Name	AOS2024
Shell Reference	16560-182
Active Matter, wt%	31.1
Molecular Weight	424
Unsulfonated Organics, wt%	0.8
pH, as is	11.7
Sodium Sulfate, wt%	0.4
Sodium Chloride, wt%	0.002

Surfactant Solution Preparation:

1. To a flask add 1000 grams of the following ingredients:
    - 10.00 grams NaCl ($10/1000 = 0.01 = 1wt\%$)
    - 3.22 grams AOS2024 ($3.22 \times 0.311/1000 \sim 0.001 = 0.1wt\%active$)
    - 986.88 grams distilled water
2. Mix and heat to $\sim 80degC$ for 30 minutes.
3. Lower heat to $\sim 60degC$ and use at this temperature.

8.3 Appendix C: Steam Quality Calculation

To calculate the amount of water or steam needed to have a desired quality at the sandface, an enthalpy balance is used. Pertinent saturated steam data, given in Table 8.3, is taken from Table C-1 of "Introduction to Chemical Engineering Thermodynamics" 3rd edition, McGraw Hill, by Smith and Van Ness, which were reproduced from Combustion Engineering, Inc. 1940.

Table 8.3: Saturated Steam Data

Temperature F	Pressure psia	Liq SpVol cuft/lbm	Vap SpVol cuft/lbm	Liq SpH BTU/lbm	Vap SpH BTU/lbm
62	0.2749	0.01604	1129.7	30.06	1088.0
72	0.3883	0.01606	814.9	40.04	1092.3
82	0.5409	0.01608	595.8	50.02	1096.6
92	0.7429	0.01611	441.7	59.99	1100.9
315	83.50	0.01760	5.257	285.1	1183.9
320	89.65	0.01765	4.915	290.3	1185.3
325	96.16	0.01771	4.601	295.5	1186.6

For nomenclature, the following will apply:

- mass fraction steam before steam-water junction: X_{st}
- mass fraction water before steam-water junction: $X_{wa} = 1 - X_{st}$
- enthalpy of water at a given temperature P: H_{waP}
- enthalpy of steam at a given temperature P: H_{stP}
- quality (mass fraction) of steam after steam-water junction: Γ

Using ambient temperature of $72degF$ and steam temperature of $320degF$, then:

- energy of water before steam-water junction: $X_{wa} * H_{wa72}$
- energy of steam before steam-water junction: $X_{st} * H_{st320}$
- energy of system after steam-water junction: $\Gamma * H_{st320} + (1 - \Gamma) * H_{wa320}$

so,

- $X_{wa} * H_{wa72} + X_{st} * H_{st320} = \Gamma * H_{st320} + (1 - \Gamma) * H_{wa320}$

Rearranging for X_{wa}, with an initial subtitution of $X_{st} = 1 - X_{wa}$, then:

- $X_{wa} = \frac{H_{st320} - (\Gamma * H_{st320} + (1-\Gamma) * H_{wa320})}{H_{st320} - H_{wa72}}$

and,

- $X_{st} = 1 - X_{wa}$

For Example:

1. if 40% steam-quality is wanted at the sandface;
    - $X_{wa} = \frac{1185.3-(0.40*1185.3+0.60*290.3)}{1185.3-40.04} = 0.469$
    - $X_{st} = 0.531$
    - The steam rate before the junction is (fixed) at $4.36ml/min$ cwe
    - The total fluid injected is $4.36/0.531 = 8.21ml/min$ (due to roundoff error, the amount used was $\sim 8.23ml/min$)
    - The water before the junction is: $8.21 - 4.36 = 3.85ml/min(\sim 3.87$ used)
    - The water after the junction is: $8.21 * 0.60 = 4.93ml/min(\sim 4.94$ used)
    - The steam after the junction is: $8.23 * 0.40 = 3.28ml/min(\sim 3.29$ used)
2. if 60% steam-quality is wanted at the sandface;
    - $X_{wa} = \frac{1185.3-(0.60*1185.3+0.40*290.3)}{1185.3-40.04} = 0.313$
    - $X_{st} = 0.687$
    - The steam rate before the junction is (fixed) at $4.36ml/min$ cwe
    - The total fluid injected is $36/0.687 = 6.35ml/min$ (due to roundoff error, the amount used was $\sim 6.34ml/min$)
    - The water before the junction is: $6.35 - 4.36 = 1.99ml/min(\sim 1.98$ used)
    - The water after the junction is: $6.35 * 0.40 = 2.54ml/min$
    - The steam after the junction is: $6.35 * 0.60 = 3.81ml/min(\sim 3.80$ used)
3. if 80% steam-quality is wanted at the sandface;
    - $X_{wa} = \frac{1185.3-(0.80*1185.3+0.20*290.3)}{185.3-40.04} = 0.156$
    - $X_{st} = 0.844$
    - The steam rate before the junction is (fixed) at $4.36ml/min$ cwe
    - The total fluid injected is $4.36/0.844 = 5.17ml/min$ (no problem with roundoff error)
    - The water before the junction is: $5.17 - 4.36 = 0.81ml/min$
    - The water after the junction is: $5.17 * 0.20 = 1.03ml/min$
    - The steam after the junction is: $5.17 * 0.80 = 4.14ml/min$

The exact ambient temperature varied during an experiment, but the associated error is small. For example:

1. For the 40% quality calculation;
    - $X_{wa} = 0.469$ when ambient$= 72degF$
    - $X_{wa} = 0.465$ when ambient$= 62degF$
    - $X_{wa} = 0.473$ when ambient$= 82degF$
2. For the 60% quality calculation;
    - $X_{wa} = 0.687$ when ambient$= 72degF$
    - $X_{wa} = 0.690$ when ambient$= 62degF$
    - $X_{wa} = 0.684$ when ambient$= 82degF$

3. For the 80% quality calculation;

   - $X_{wa} = 0.156$ when ambient= $72degF$
   - $X_{wa} = 0.155$ when ambient= $62degF$
   - $X_{wa} = 0.158$ when ambient= $82degF$

8.4 Appendix D: Nitrogen Mole% Injected

mole = gram-mole

1. The flow rate of nitrogen is constant at 160 cc/min (standard conditions).

   That is, since:

   - The mass flow meter reading is: 0.08 Std.Liter/minute
   - The meter calibration is : actual rate (cc/min) = 2000 * reading (SL/min).

   then:

   - The actual rate (cc/min) = 2000 * 0.08 = 160 cc/min.

2. The nitrogen mole rate is constant at 0.007143 gmole/min.

   That is, since:

   - The volume of one mole (at standard conditions) is: 22400 cc/mole.

   then:

   - The mole rate (mole/min) = 160 * (1/22400) = .007143 mole/min.

3. The water rate into the steam generator is constant at 4.36 ml/min.

4. The water mole-rate is constant at 0.242 mole/min.

   That is, since:

   - The molecular weight of water is: 18 grams/mole.
   - The density of water is: 1 gram/ml.

   then:

   - The mole rate (mole/min) = 4.36 * (1/18) x (1) = 0.242 mole/min.

5. The nitrogen/steam mole ratio at 100% quality is 0.0295, or 2.95 percent.
   That is:

   - 0.007143/0.242 = 0.0295 = 2.95%

6. The nitrogen/steam mole ratio at 80% quality is 0.0311, or 3.11 percent.
   That is, since:

   - The rate from the steam generator is: 4.36 cc/min cwe
   - The rate of water (ambient) injected is: 0.81 cc/min
   - The rate of steam (gas) reaching the sandface is: 4.14 cc/min cwe (95%)
   - The rate of water reaching the sandface is: 1.03 cc/min

   then:

   - (4.36/4.14) * 0.0295 = 0.0311 = 3.11%

7. The nitrogen/steam mole ratio at 60% quality is 0.0338, or 3.38 percent.
   That is, since:

   - The rate from the steam generator is: 4.36 cc/min cwe
   - The rate of water (ambient) injected is: 1.98 cc/min
   - The rate of steam (gas) reaching the sandface is: 3.80 cc/min cwe (87%)
   - The rate of water reaching the sandface is: 2.54 cc/min

   then:

   - (4.36/3.80) * 0.0295 = 0.0338 = 3.38%

8. The nitrogen/steam mole ratio at 40% quality is 0.0391, or 3.91 percent.

   That is, since:

   - The rate from the steam generator is: 4.36 cc/min cwe
   - The rate of water (ambient) injected is: 3.87 cc/min
   - The rate of steam (gas) reaching the sandface is: 3.29 cc/min cwe (75%)
   - The rate of water reaching the sandface is: 4.94 cc/min

   then:

   - (4.36/3.29) * 0.0295 = 0.0391 = 3.91%

8.5 Appendix E: Nitrogen as an Ideal Gas

From page 87 (of "Introduction to Chemical Engineering Thermodynamics" 3rd edition, McGraw Hill, by Smith and Van Ness) Pitzer's correlations are given for determination of the compressibility factor.

- $z = 1 + (BP_c/RT_c) \times (P_r/T_r)$
- $(BP_c/RT_c) = B_o + \omega B_1$
- $B_o = 0.083 - (0.422/T_r^{1.6})$
- $B_1 = 0.139 - (0.172/T_r^{4.2})$

where

- T_c= critical temperature = 126.2 K (from page 569 of above text)
- P_c= critical pressure = 33.5 atm (from page 569 of above text)
- ω= accentric factor = 0.040 (from page 569 of above text)
- T_r= reduced temperature = 3.43 (from 433/126.2, where 320F=433K)
- P_r= reduced pressure = 0.182 (from 6.1/33.5, where 89psia=6.1atm)

so, under our conditions,

- $B_o = 0.083 - 0.422/3.43^{1.6} = 0.02427$
- $B_1 = 0.139 - 0.172/3.43^{4.2} = 0.138$
- $BP_c/RT_c = 0.02427 + 0.040 \times 0.138 = 0.0298$
- $z = 1 + 0.0298 \times (0.182/3.43) = 1.001$

therefore,

SINCE Z=1.001, NITROGEN IS AN IDEAL GAS UNDER OUR CONDITIONS

8.6 Appendix F: Steam and Nitrogen Gas Volumes Injected

As shown in Appendix E, nitrogen acts as in ideal gas under our conditions. From Appendix C the specific volume of steam under our conditions is 4.915 cubic-ft per pound-mass. Our conditions are 89 psia and 320 deg F.

Conversions and constants:

- 1lbm = 453.6 grams
- 1cuft = $(30.48cm)^3$
- 1gram water = 1 cc water (ambient)
- R (Gas Constant) = 82.05 (cc-atm/gmole-K)
- nitrogen rate = 0.007143 gmole/min

Using the above conversions, with the knowledge that the steam-rate is 4.36 ml/minute cwe, then:

- Volume of steam injected (100% quality case): $4.36 \times 1 \times 4.915 \times (1/453.6) \times (30.48)^3 =$ 1337cc/min = 0.89 PV/min
- Volume of steam injected (80% quality case): $1337 \times (4.14/4.36) =$ 1270cc/min = 0.85 PV/min = 95% of 100% quality case
- Volume of steam injected (60% quality case): $1337 \times (3.81/4.36) =$ 1168cc/min = 0.78 PV/min = 88% of 100% quality case
- Volume of steam injected (40% quality case): $1337 \times (3.28/4.36) =$ 1006 cc/min = 0.67 PV/min = 75% of 100% quality case
- Volume of nitrogen injected: $82.05 \times (433/6.1) \times 0.007143 =$ 41.60cc/min

Nitrogen/Steam volume ratio:

- 100% quality case: 41.60/1337 = 0.0311 = 3.11%
- 80% quality case: 41.60/1270 = 0.0328 = 3.28%
- 60% quality case: 41.60/1168 = 0.0356 = 3.56%
- 40% quality case: 41.60/1006 = 0.0414 = 4.14%

Note: The above volume ratios are very close to the mole ratios (Appendix D) of 2.95% (100% quality), 3.11% (80% quality), 3.38% (80% quality), and 3.91% (40% quality), which shows that the mole ratios are good indications of the actual volumes ratios. Since nitrogen acts and an ideal gas under our conditions (Appendix E), this also indicates that steam is essentially ideal under our conditions.

8.7 Appendix G: Material Balance of Injected and Produced Water

RUN 6a (first 13 slugs)

SLUG	FLUID PRODUCED ml	PROD. TIME min		FLUID INJECTED ml
1	550	33	150+33*8.23 =	422
2	200	26	150+26*8.23 =	364
3	715	60	150+60*8.23 =	644
4	550	50	150+50*8.23 =	562
5	550	49	150+49*8.23 =	553
6	630	57	150+57*8.23 =	619
7	580	54	150+54*8.23 =	594
change-over	(volumes not recorded)			
8	360	36	150+36*6.34 =	378
9	600	60	150+60*6.34 =	530
10	520	60	150+60*6.34 =	530
change-over	(volumes not recorded)			
11	500	56	150+56*5.17 =	439
12	470	59	150+59*5.17 =	455
13	460	60	150+60*5.17 =	460
TOTALS	6685			6550

difference: 135 cc (~2%) which is within the error of the pump calibration and the produced-volume determinations.

RUN 7 (first 11 slugs)

SLUG	FLUID PRODUCED ml	PROD. TIME min	FLUID INJECTED ml
1	790	63	150+63*8.23 = 668
2	790	73	150+73*8.23 = 751
3	900	85	150+85*8.23 = 850
4	1030	109	150+109*8.23= 1047
5	1050	108	150+108*8.23= 1039
6	680	60	150+60*8.23 = 644
change-over	440	91	91*4.36 = 397
7	460	108	150+108*4.36= 620
8	500	103	150+103*4.36= 599
9	(volumes not recorded)		
change-over	560	96	96*8.23 = 790
10	700	57	150+57*8.23 = 619
11	660	59	150+59*8.23 = 636
TOTALS	8560		8660

difference: 100 cc (~1%) which is within the error of the pump calibration and the produced-volume determinations.

8.8 Appendix H: Conversion of Pressure Data to Pressure-Drop Plots

1) At the pangea prompt type the following:

```
pangea> awk -f awk.run7 b:press07.dat
```

The raw data file is b:press07.dat, which looks like the following except that the actual file is longer and does not have column headings.

time	bp	dp1a	dp1b	dp1c	dp1d	dp2	dp3	dp4	dptot
21:00:15	68.2384	0.0085	0.0245	0.3340	0.7141	3.2759	3.5935	1.6065	9.557
21:01:10	68.1435	0.0222	0.0236	0.3218	0.7250	3.2161	3.5982	1.8066	9.713
21:02:04	67.8508	0.0136	0.0236	0.3326	0.7280	3.2751	3.5734	1.3332	9.279
21:02:59	68.1758	0.0117	0.0195	0.3237	0.7355	3.2913	3.4142	2.0295	9.825

The program used to convert the data, awk.run7, looks like:

```
{
   if ($1 ~ /:[0123456789][0123456789]:/)
     {
      hour=substr($1,1,2) + 0.
      if (hour<23 && NR>1570)
      { hour = hour + 24 }
      min =substr($1,4,2) + 0.
      sec =substr($1,7,2) + 0.
      time=hour + min/60. + sec/3600.
      if ($3<0.00)
      { $3=0.00 }
      if ($4<0.00)
      { $4=0.00 }
      if ($5<0.00)
      { $5=0.00 }
      if ($6<0.00)
      { $6=0.00 }
      if ($7<0.00)
      { $7=0.00 }
      if ($8<0.00)
      { $8=0.00 }
      if ($9<0.00)
      { $9=0.00 }
      if ($10<0.00)
      { $10=0.00 }
      print time"    "$2  > "bp.07"
      print time"    "$3  > "dp1A.07"
      print time"    "$4  > "dp1B.07"
      print time"    "$5  > "dp1C.07"
      print time"    "$6  > "dp1D.07"
      print time"    "$3 + $4 + $5 + $6  > "dp1.07"
      print time"    "$7  > "dp2.07"
```

```
                print time"     "$8  > "dp3.07"
                print time"     "$9  > "dp4.07"
                print time"     "$10 > "dpt.07"
                }
        }
```

The above awk file creates a file (dp2.07) which looks like the following, except that the actual is longer and does not have column headings.

```
                 time       dp2

                21.0042    3.2759
                21.0194    3.2161
                21.0344    3.2751
                21.0497    3.2913
```

2) At the pangea prompt type the following:

```
pangea> gps run7c.com
```

The graphing program, gps, was written by R.C. Wattenbarger. A typical command file, run7c.com, looks like the following.

```
{ Make a landscape plot
translate 8.5 0
rotate 90
size 7 4
line   1 2 3 4 5
symbol  0 0 0 0 0
linefat !50 1.
ticsize .05  .025
axis on
axismethody 0
permajory 7
boxtic on
ymin 0 ymax  12.0
xmin 23.5 xmax 27.1
{ give each data set a name
 name 1 "1st Section"
 name 2 "2nd Section"
 name 3 "3rd Section"
 name 4 "4th Section"
{read xy saturations { read file dat.xy
read xy dp1.07
read xy dp2.07
read xy dp3.07
read xy dp4.07
labelsize 20
labelx "Time   (hrs)"
```

```
labely "Pressure Drop   (psi)"
at 2 2 xy      { write xy graph
{ Set label strings
stringsize 15.
 atobj .03 .879 string "Surfactant: AOS2024"
stringsize 15.
 atxy 23.9 5.6 string "10% PV Slug", 1
stringsize 15.
 atxy 23.9 5.0 string "Slug 10", 1
stringsize 15.
 atxy 25.0 5.6 string "10% PV Slug", 1
labelsize 12
atobj 0.7  0.96 legend  { place legend
{atxy 1 1  string "" , 1b , 45  {place string
```

8.9 Appendix I: Conversion of Pressure Data to Pressure-Profile Plots

1) At the pangea prompt type the following:

```
pangea> awk -f awk.ppf9 b:press07.dat
```

where b:press07.dat is the raw data file (example given in Appendix H), and awk.ppf9 is the program used to convert the data, which looks like:

```
{
  if ($1=="20:36:28")
   {
       print 5 > "ppf9.07"
       print 0"     "($2+$10)  > "ppf9.07"
       print 16"    "($2+$7+$8+$9)  > "ppf9.07"
       print 32"    "($2+$8+$9)  > "ppf9.07"
       print 52"    "($2+$9)  > "ppf9.07"
       print 72"    "$2    > "ppf9.07"
   }
  if ($1=="20:48:21")
   {
       print 5 > "ppf9.07"
       print 0"     "($2+$10)  > "ppf9.07"
       print 16"    "($2+$7+$8+$9)  > "ppf9.07"
       print 32"    "($2+$8+$9)  > "ppf9.07"
       print 52"    "($2+$9)  > "ppf9.07"
       print 72"    "$2    > "ppf9.07"
   }
  if ($1=="21:00:15")
   {
       print 5 > "ppf9.07"
       print 0"     "($2+$10)  > "ppf9.07"
       print 16"    "($2+$7+$8+$9)  > "ppf9.07"
       print 32"    "($2+$8+$9)  > "ppf9.07"
       print 52"    "($2+$9)  > "ppf9.07"
       print 72"    "$2    > "ppf9.07"
   }
  if ($1=="21:12:08")
   {
       print 5 > "ppf9.07"
       print 0"     "($2+$10)  > "ppf9.07"
       print 16"    "($2+$7+$8+$9)  > "ppf9.07"
       print 32"    "($2+$8+$9   > "ppf9.07"
       print 52"    "($2+$9)  > "ppf9.07"
       print 72"    "$2    > "ppf9.07"
   }
}
```

The above program makes a created file (ppf9.07) look like the following.

```
5
0     65.3408
16    64.2705
32    61.8739
52    62.5219
72    62.5759
```

2) As shown in Appendix H, gps can now be used to plot graphs.

8.10 Appendix J: Conversion of Thermocouple Data to Temperature Plots

1) At the pangea prompt type the following:

```
pangea> awk -f awk.trow1 b:temp07.dat

pangea> awk -f awk.trow2 b:temp07.dat

pangea> awk -f awk.trow3 b:temp07.dat
```

where b:temp07.dat is the raw data file, which looks like the following, except that the actual file is longer.

```
03:05:46
159.82 158.29  26.52 158.06  25.13 157.44  24.64 158.44 157.82 158.54
158.37 158.47 157.59 157.92 156.46 156.09 156.13 155.71 154.75 155.25
152.38 107.81 222.42 159.62
03:06:41
159.72 157.34  26.50 157.27  25.18 156.89  24.76 158.07 157.65 158.32
158.13 158.30 157.39 157.77 156.30 155.96 156.04 155.62 154.71 155.22
152.48 108.27 219.92 156.25
```

(24 thermocouples, 21 along pack, 1 at the outlet, 1 at the steam generator, 1 at the inlet)

The programs awk.trow1, awk.trow2, and awk.trow3 are used to convert the data. They look like the following.

awk.trow1

```
        {
          if ($1 ~ /:[0123456789][0123456789]:/)
            {
             hour=substr($1,1,2) + 0.
             if (hour<23 && NR>1570)
             { hour = hour + 24 }
             min =substr($1,4,2) + 0.
             sec =substr($1,7,2) + 0.
             time=hour + min/60. + sec/3600.
             }
          else
            {
             if ((NR-2)%4==0)
                {
                 print time"    "$1 > "t1.07"
                 print time"    "$2 > "t2.07"
```

```
                print time"    "$3 > "t3.07"
                print time"    "$4 > "t4.07"
                print time"    "$5 > "t5.07"
                print time"    "$6 > "t6.07"
                print time"    "$7 > "t7.07"
                print time"    "$8 > "t8.07"
                print time"    "$9 > "t9.07"
                print time"    "$10 > "t10.07"
                }
            next
            }
      }
```

awk.trow2

```
      {
        if ($1 ~ /:[0123456789][0123456789]:/)
          {
           hour=substr($1,1,2) + 0.
           if (hour<23 && NR>1570)
           { hour = hour + 24 }
           min =substr($1,4,2) + 0.
           sec =substr($1,7,2) + 0.
           time=hour + min/60. + sec/3600.
           }
        else
          {
           if ((NR-3)%4==0)
              {
               print time"    "$1 > "t11.07"
               print time"    "$2 > "t12.07"
               print time"    "$3 > "t13.07"
               print time"    "$4 > "t14.07"
               print time"    "$5 > "t15.07"
               print time"    "$6 > "t16.07"
               print time"    "$7 > "t17.07"
               print time"    "$8 > "t18.07"
               print time"    "$9 > "t19.07"
               print time"    "$10 > "t20.07"
               }
           next
           }
      }
```

awk.trow3

```
      {
        if ($1 ~ /:[0123456789][0123456789]:/)
          {
```

```
            hour=substr($1,1,2) + 0.
            if (hour<23 && NR>1570)
            { hour = hour + 24 }
            min =substr($1,4,2) + 0.
            sec =substr($1,7,2) + 0.
            time=hour + min/60. + sec/3600.
            }
         else
          {
           if ((NR-4)%4==0)
             {
              print time"    "$1 > "t21.07"
              print time"    "$2 > "t22.07"
              print time"    "$3 > "t23.07"
              print time"    "$4 > "t24.07"
              }
            next
            }
      }
```

The above awk files create two column file for each thermocouple which are similar to the file in Appendix H, except that column two is temperature in degrees Celsius.

2) The graphing program gps, as shown in Appendix H, can now be used to plot graphs

8.11 Appendix K: Conversion of Thermocouple Data to Temperature-Profile Plots

1) First edit the data to keep only the five or six times needed. An alternate approach would be similar to that used in Appendix I. The result of editing gives a data file that looks like:

```
05:59:48
156.02 154.72 143.22 155.37 147.78 149.82 148.52 148.54 150.12 151.01
150.16 151.36 149.93 150.66 149.77 149.97 150.86 149.27 150.86 151.17
167.29  42.68 264.22 159.44
06:12:48
166.90 163.59 163.18 163.61 163.65 162.96 161.42 163.56 155.29 159.50
161.10 155.76 158.18 158.39 151.53 148.65 148.10 151.91 146.81 146.58
160.50 110.36 245.34 165.49
06:23:48
169.03 163.09 163.05 162.88 163.32 162.38 162.09 162.97 160.75 162.14
161.68 161.41 159.89 159.97 158.16 157.34 156.96 155.84 151.83 155.43
161.09 125.36 240.77 164.16
```

2) At the pangea prompt type the following:

```
pangea> awk -f awk.tpf2 slug2.dat
```

where slug2.dat is the (modified) raw data file, above, and awk.tpf2 is the program used to convert the data into gps form. It look like:

```
{
   if (NF==10 && (NR-2)%4==0)
     {
          print 19 > "tpf2.01"
          print 2"    "$2 > "tpf2.01"
          print 4"    "$3 > "tpf2.01"
          print 6"    "$4 > "tpf2.01"
          print 8"    "$5 > "tpf2.01"
          print 10"    "$6 > "tpf2.01"
          print 12"    "$7 > "tpf2.01"
          print 15"    "$8 > "tpf2.01"
          print 18"    "$9 > "tpf2.01"
          print 21"    "$10 > "tpf2.01"
      }
   if (NF==10 && (NR-3)%4==0)
     {
          print 24"    "$1 > "tpf2.01"
          print 28"    "$2 > "tpf2.01"
          print 32"    "$3 > "tpf2.01"
          print 36"    "$4 > "tpf2.01"
          print 40"    "$5 > "tpf2.01"
          print 44"    "$6 > "tpf2.01"
```

```
                        print 49"    "$7 > "tpf2.01"
                        print 54"    "$8 > "tpf2.01"
                        print 59"    "$9 > "tpf2.01"
                        print 64"    "$10 > "tpf2.01"
                 }
        }
```

2) As shown in Appendix H, gps can now be used to plot graphs.

8.12 Appendix L: Permeability Determination of Linear Model

permeability = 57.0 * (flowrate/pressure-drop)

Input Pressure psi	Output Pressure psi	Production Time sec	Produced Volume ml	Flow Rate ml/sec	Pressure Drop psi	Calculated Perm. Darcy
20	11.2	103	100	0.971	0.648	85.4
15	10.3	166	100	0.602	0.394	87.1
10	8.0	523	1000	0.191	0.134	81.1
1	0.0	319	100	0.313	0.208	85.9
19	13.1	132	100	0.758	0.503	85.8
19	13.1	134	100	0.746	0.491	86.6
11	8.0	224	100	0.446	0.319	79.7
12	10.8	384	100	0.260	0.029	510.1
	****zero	calibration	error:	value	not	used****
17	11.8	150	100	0.667	0.416	91.2
23	13.4	174	200	1.149	0.749	87.5
18	12.6	120	100	0.833	0.336	141.3
	****leak	detected:	value	not	used****	
18	12.4	241	200	0.830	0.428	110.5
18	12.3	125	100	0.800	0.415	110.0
25	14.0	300	415	1.383	0.683	115.5
25	13.8	300	409	1.363	0.682	114.0
25	8.4	150	275	1.833	1.019	102.5
25	8.4	150	270	1.800	0.998	102.8

```
---------------------------------------------
       mean :  95.0 plus or minus 12.7 Darcy
---------------------------------------------
```

8.13 Appendix M: Summaries of Papers Cited

- 1960's

****

Fried, A.N., "The Foam-Drive Process for Increasing the Recovery of Oil", USBM 5866, 1961

Discussion of Foam-Drive Mechanism: Foam injected into the sand surrounding a well bore first disperses through the largest pore channels, presumably those which have been flushed of their oil content. With movement of foam into larger voids and channels, the resistance to flow increases rapidly owing to the high effective viscosity of the foam and to the blocking tendencies of the constrictions along the flow paths. As flow resistance builds up and injection pressure is increased, smaller bubbles are forced into the smaller channels thereby causing a foam bank to be developed. Owing to greater resistance to flow at the injection well relative to resistance to flow in the downstream region of the reservoir, the pressure in the latter region is reduced. Thus, in effect, the pressure gradient across the foam front is increased. With establishment of a mobile foam front, continuous flow paths that had previously carried the greatest part of the total flow of the prior displacing medium become blocked or restricted resulting in 1) diversion of flow to small unflused flow channels 2) migration of a medium exhibiting high effective viscosity, and 3) presence of a high-pressure gradient at the invading front. Scavenging of residual oil by foam creates an oil bank or zone of high oil saturation ahead of the foam front.

Foams exhibit markedly greater viscosities than the separate viscosities of the gaseous and liquid phases of which they are constituted.

Since the surface-active agents occur as adsorbed molecules in the gas-liquid interfaces forming foam bubble wall, the tendency to be adsorbed by rock-mineral surfaces is more strongly opposed than in surfactant solution flooding.

The presence of a discontinuous gas phase formed by foam increases the gas saturation of the sands without creating high gas-oil relative permeability ratios. Thus, to some extend, foam tends to produce the effect of a trapped gas.

Using a Fann VG meter, he shows apparent viscosity decreasing with increasing drainage from a foam. This is the same as saying that the apparent viscosity should decrease as quality increases.

Using a capillary tube viscometer, tests showed that the viscosity of a foam flowing in capillary tubes varies almost directly as the diameter of the flow channel. Presumeably, for a given size of capillary, flow resistance should increase as bubble size decreases in a foam of a given expansion factor. This is qualitatively verified by the study by not quantitatively correlated (interesting, this is just what Hirasaki and Lawson's 1985 paper reported, ie that finer textures are more resistive).

(my note: this paper contains many more interesting studies including oil displacement and electrokinetic effects, the paper is quite extensive and thorough, and would be worth reading further).

****

Bernard, G.G. and Holm L.W., "Effect of Foam on Permeability of Porous Media to Gas", SPEJ 267-274 , September 1964

Laboratory experiments were conducted to determine the effect of foam on gas flow in porous media. Foam was found to be exceedingly effective in reducing the permiability of porous media to gas, with reductions to less than 1% of the specific permeability. The greater permeability reduction was obtained in the higher (initial) permeability media. The presence of oil decreased the effectiveness of foam in reducing gas permeability. Fluids used in the experiments were water, 1% or 11% brines, aqueous solutions of foaming agents, nitrogen gas and West Texas crude oil. Cores ranged in sizes from 6" to 30" (with permeabilities from 100 to 250 md and porosities of 20%), and sandpacks from 1 to 30 ft long (with permeabilities from 3000 to 150,000 md and porosities of 40%) were used. Both simultaneous and alternating slugs were employed. (no mention of a difference in results due to injection scheme). At pressure gradients of 4 to 20 psi/ft permeability reduction with foam was easy to maintain (22 days), but when the pressure drop was incresed to 40 psi/ft, the foam bank broke down and gas permeability rose rapidly. The following conclusions were drawn: 1) foam stability increases as specific permeability of the porous body decreases; and 2) in porous structures with permeabilities less than 1 darcy, it should be possible to generate and maintain a foam bank for long time periods. Foam was found to be resistant to relatively high pressure gradients, especially in lower permeability sands. Because foam is thermodynamically unstable, permanent underground plugging action can best be attained by continuous foam generation. This can be done by injecting, continuously or intermittetly, small volumes of foaming agent solution into the gas stream.

The data (No Oil) show that at gas saturations up to 50% , foams made from solutions containing 0.01, 0.1, or 1% surface active agent all reduce the gas permeability of a 3890 md sand to less than 1 md. At higher gas saturations the permeability to gas decreases as surface active agent concentrations increases. So even dilute foaming agent solutions can generate foam which for most practical purposed block gas flow. The results show that for three agent concentrations (0.01, 0.1, and 1%), at solution injection rates of 0.3 to 20 B/D/sq ft, gas permeabiltiy remained at or near zero. This is especially remarkable since gas saturations was varied from 30 to 77%.

It was found that when foam was present in a core under a given pressure gradient, the water and gas saturations in the core were the same as in the normal case where there was not foam. So foam has essentially no effect on gas saturation. But at a given saturation, foam had a marked effect on gas permeability.

Comparison with results obained when oil was not present in the packs, data shows that oil decreased the ability of foam to reduce gas permeability and to maintain it at low values. On the other hand, the presence of salts in water do not appear to reduce the effectiveness of foam to an appreaciable degree.

****

Bernard, G.G, Holm, L.W., Jacobs, W.L., "Effect of Foam on Trapped Gas Saturation and on Permeability of Porous Media to Water" SPEJ Dec 1965 p 295

The effect of foam on the permeability of porous media to water was studied as a function of foaming agent concentration, specific permeability, pressure gradient, length of a porous medium and its oil saturation. At a given fluid saturation in a porous medium, the permeability to water was found to be the same whether foam was present or not. (however, in a sense one can still say that the foam lowered the water permeabilty since the foam increased the gas saturation and hence lowered the water saturation. The point is that then water relative perm was described by Darcy's Law.) The presence of oil reduced the capability of most foaming agents to decrease the permeabilty of a porous medium to water. The effect of foam was found to persist in long pores at moderately high reservour temperatures and during the passage of many pore volumes of surfactant-free water.

The porous media consisted of consolidated sandstone cores (6 to 36 in long), and unconsolidated sand packs (3 to 30 ft long). The consolidated cores had permeabilities of 32 and 1000 md and porosities of about 20 percent. The sand packs had permeabilties of 3500 to 211,000 md and porosities of about 40 percent.

For two foaming agents (not disclosed) at conc. of 0.01, 0.1, and 1.0% the presence of foam did not affect the relationship that the relative permeability to water is a singled valued function of the saturation. The explanation given is "foam is an agglomeration of gas bubbles separated by liquid films; the gas is discontinuous while the liquid is continuous. Since the liquid films contact each other, they can conduct liquid; therefore it is not unreasonable that at a given liquid saturation in a porous medium there should be essentially the same permeability to water, whether foam is present or not."

Data indicate that 1) trapped gas saturation is higher in the presence of foam than in its absence and 2) trapped gas saturation is higher in an all-water system than in a system containing both oil and water.

Changes in pressure gradient did not affect the relative permeability to water in the presence of foam.

Foam stability of six surfactants were checked for their abiltiy to withstand the erosive action of injected water. The results show that even though the injected water lowered the trapped gas saturation from 70%(water case with no oil) to 19%, it took 24 pore volumes to do so, indicating that for the particular surfactant checked, that the generated foam resisted the erosive action of the injected water. (with no foaming agent, the gas saturation was 12%).

Data indicates that (using 30 ft long packs) foam remains in a long porous medium which contains oil and brine even after passage of many pore volumes of surfactant free water. (temp of 140F).

****

Sharma, S.K. "A Study of the Microscopic Behavior of the Foam Drive Method", MS Report Stanford University, December 1965

Used single or multilayered matrices of glass beads sandwiched between glass plates and nylon or polythene nets sandwiched between glass plates. Air was used to generate foam out-situ. It was observed that the size and shape of bubbles depended on: 1) the type of surfactant 2) the concentration of surfactant and 3) foam quality. After the cessation of flow, bubbles had a tendency to degenerate into larger bubbles, which could be retarted by increasing surfactant concentration from 0.1 to 1%. Large variations in bubble size were observed as the foam entered the porous media resulting in a very nonuniform distribution. During flow the bubbles flow individually. Fast injection produced fingers and lower oil recovery than slow injection (of preformed air-foam) which gave a piston like front.

****

Marsden, S.S, and Khan, S.A, "The Flow of Foam Through Short Porous Media and Apparent Viscosity Measurements", SPEJ March 1966 p 17

Foam produced in a generator with air injection (produced external to core). AC resistivity was used to determine liquid saturation while the foam was flowing. Perm measured with air and porosity with liquid saturation. The surfactant Aerosal MA (sodium dihexylsufosuccinate) was used at concentrations of either 1.0 or 0.1 per cent in distilled water. Foam flow rate was measured at atmospheric pressure by observing the time required to fill a weighed 25 ml pipette, which also allowed calculation of foam quality. Foam texture was described in terms of per cent transmission of white light. Apparent viscosity was measured in three different methods a) Fann VG meter b) capillary tube viscometer and c) Bendix Ultraviscoson. (warns that results from different researchers can be compared only with caution since conditions are different).

Since the method of foam preparation affects the texture, results obtained by agitation or violent mixing of the two phases in a large container should not be compared with those obtained by flow of the two phases through a porous medium. Foams that break or drain readily should also not be compared with those having long lives unless both are being constantly regenerated by some high shear stress method.

Depending of the methos of measuring foam apparent viscosity, different results were obtained. Using a modified Fann VG Meter, the apparent viscosity increases almost linearly with foam quality (this is interesting since using a Fann VG model 31 meter, Fried found visosity to decrease linearly with drainage, which is to say viscosity decreased with quality, which is the opposite result). However, using a Bendix Ultraviscoson, the apparent viscosity was essentially independent of foam quality.

Points out that quality increases towared effluent end by expansion of gas. Found that apparent viscosity decreases with increasing shear rate. Found only a slight increase in apparent viscosty with concentration over the range of 0.1 to 1.0 per cent. Found gas relative permeabilities of less than 1 per cent.

It is quite possible that the foam produced by our genèrator was appreaciable finer than the pores of the coarser porous media, and thus, that it was more mobil than the same foam in the tighter porous media

****

Marsden, S.S., Jr., Eerligh, J.J.P., Albrecht, R.A., and David A., "Use of Foam in Petroleum Operations", The Proceedings of the Seventh World Petroleum Congress, April 1967

Foams are thermodynamically unstable systems because they always contain more than a minimal amount of gas-solution interface. This interface represents surface free energy, the amount of which can be estimated from a knowledge of the surface tension of the solution and the interfacial area of the foam. Whenever a foam membrane breaks and the liquid coalesces, there is a decrease in the surface free energy.

The relative amount of the two phases is a critical factor (quality). Of equal importance is bubble texture. All results to date suggest that foams behave like non-Newtionian fluids. Thus true viscosity cannot be measured for foams but shear stresses can be measured at a number of shear rates and apparent viscosities calculated. In rheological terminology, foams behave like pseudoplastic fluids while others behave like Bingham plastic. The reasons are not known.

Thorough mixing of the gas, liquid and solute is very important; without this only a foamy condition in parts of the flow system or at best a foam of variable properties is attained.

****

Holm, L.W., "The Mechanism of Gas and Liquid Flow Through Porous Media in the Presence of Foam" SPEJ Dec 1968 p 359

This study shows that in the presence of foam, gas and liquid flow separately through porous media representative of reservoir rock. These results were obtained using tracer techniques to measure the flow of the gas and liquid comprising the foam. Foam does not flow through the porous media as a body even when the liquid and gas are combined outside the system and injected as foam. Instead, the liquid and gas forming the foam separate as the foam films break and then re-form in the porous system. Liquid moves through the porous media via the film network of the bubbles and gas moves progressivley through the system by breaking and re-forming bubbles throughout the length of the flow path. The flow rates of the gas and liquid are a function of the number and strength of the films in the porous medium. There is no free flow of gas, i.e , no continous gas phase.

"Normally, when two immiscible phases (gas and liquid) flow concurrently through a porous medium, each phase follows separate paths or channels. At given saturations of the two phases, a certain number of channels are available to each phase, and as saturations change, the number and configuration of the channels available for each phase is a function of the saturation of that phase only, and the flow of each phase can be described by Darcy's law. When foam is present, the effective permeabiity of the porous medium to each phase is greately reduced compared with permeabilities measured in the absence of foam (refs.)"

A 2 ft long unconsolidated sandpack of 1.5" in diameter, using new sand after each run. Absolute perm of about 5 darcies.

Run 1: sandpack sat. with brine, then 2pv of 0.1% surf. solution (1.5% NaCl) injected. Then inj. air at 10psig until rate stabilized. The air was then stopped, and replaced by methane. Effluent gas was sampled. The results were that 0.7 pv of gas was produced before methane was detected, indicating that the methane was not fingering or channelling as free gas, also the gas permeability remained very low, again indicating that the flow of gas was not due to free gas. There was also a very low rate of water production, indicating that foam was not flowing as a body through the pack. The authors concluded that the gas moved through the pack by breaking and re-forming foam films.

The authors believe that diffusion is important (from small bubbles to large bubbles), and is driven by the pressure differences where delta P = 4*st/r1 minus 4*st/r2, where r1 is the radius of the smaller bubble and r2 the larger one. Diffusion, along with expansion of the foam bubbles causes large bubbles which must break to allow gas to pass through a porous medium.

Runs 2 and 3 used pregenerated foam, with run2 being at 90 percent quality and Run 3 being at 75% quality. The results (kg 6md kw 27 md in Run2[90%] vs kg 1md kw 20md in Run3[70%]) have foam-resistance being inversely proportional to foam quality.

Marsden and Khan reported that the mobility of foam DECREASES with an increase in foam quality. This study reports that mobility INCREASES with an increase if foam quality. He hypothethized that Marsdens short cores would have allowed the gas to pass through, without coalescing, possible giving such results.

****

David A. and Marsden, S.S. Jr., "The Rheology of Foam", SPE 2544 Oct 1969

Foam was generated by simultaneously injecting compressed air and an aqueous solution of a commercial foaming agent into a short porous medium. It then flowed into a capillary tube viscometer having four interchangeable glass tubes of different radii. Even though the uncorrected apparent viscosity changes with foam quality, that corrected for both slippage and foam compressibility is independent of foam quality but not of tube radius. Bubble size and bubble size distribution was measured under a microscope, both mean bubble diameter and bubble size distribution were functions of foam quality. Although the flowing foam behaved like a pseudoplastic fluid (of low gel strength), the static foam had a measureable gel strength which increased with foam quality. Apparent viscosity decreases as shear stress increases. Found the bubble size frequency distribution to be assymetrical, but approaching a normal distribution at high foam quality.

****

Kovalchuk, V.P., "The Mobility of Foam in Porous Media", Dec 1968 Stanford MS Report

The flow of foam through a series of four short porous media, of different permeabilities was investigated. The foam was generated by injecting air and a surfactant solution of 1.0% Arquad 12-50 into two foam generators, and then forcing the foam through the porous media. Controlling the flow rate of air and solution, the quality was varied from 0.54 to 0.94, which was double checked with electrical resistivity and transmission of white light. It was found that the mobility increased with increasing shear rate (flow rate). It was also possible to verify the increase of mobility with decreasing quality. (or increase in resistance as quality is increased).

The first cell contained glass spheres of 8/12 mesh, tightly packed. The second contained Ottawa sand, of 20/20 mesh. The third had clean sand of over 65 mesh and the forth loosely packed glass spheres (20/40) mesh. The absolute permeabilities were 299 darcys, 120 darcys, 34 darcys, and 299 darcys.

Foam bubbles were observed to adjust themselves to the pore size of the porous media, (he adds this makes sense since foam generators are designed with this fact in mind). Also he said that the mobility will behave in a rather irregular for if the length of the sample is not long enough for the foam to adjust its texture to the porous medium.

Note: couldn't find the exact lengths of the porous mediums used, Dr. Marsden said a few inches.

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• 1970's

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Roof, J.G., "Snap-Off of Oil Droplets in Water-Wet Pores", SPEJ March 1970

Theory indicates that for a given shape of constriction, there is a minimum size to the protruding portion of the oil that permits snap off. If the oil/solid contact angle is zero (ie 100% water wet) and if the constriction has the shape of the throat of a tore (a doughnut hole), the oil must protrude for a distance of at least seven times the throat radius before snap-off can occur. Experimental observations appear to be in accord with the theoretical predictions. Water must have a passageway into the throat to permit snap-off. Snap-off starts in the throat and appears to accelerate as the connecting neck of oil decreases in diameter. Analysis suggests that the time to give snap off in pores of a given shape should decrease as the diameter of the constriction decreases. It appears that any continuous flow of oil causes the size of snapped off droplets to be larger than those in the case of the static system.

****

Albrecht, R.A., and Marsden, S.S., "Foams as Blocking Agents in Porous Media", SPEJ page 51 March 1970

At least 50PV of filtered, de-aerated foamer solution were forced through the porous medium to achieve liquid saturations ¿ 80 percent. Afterwards air at controlled pressures was passed into the porous medium in order to generate foam in situ.

In the first series of runs, air at a given injection pressure, pi, was passed through the porous media that contained foamer solution until stabilized flow conditions prevailed. Then the injection pressure was reduced gradually until air or foam ceased to come out of the porous media. The latter pressure at which flow stops is called the blocking pressure, pb. When pi was increased to some value greater than the initial pi, flow resumes. However, upon re-decrease of injectection pressure, a new and higher blocking pressure is obtained. This process could be continued upto the maximum injection pressure available (100 psi).

In a second series of experiments, the porous media again were saturated with foamer solution, and air was injected for longer periods of time to decrease the foamer solution saturation significantly.

A plot of injection pressure vs blocking for three consentrations of Gafen FA-1 shows only a very slight effect of foamer concentration over the range 0.3 to 3.0 wt%. (not active wt percent). Although in general, the pressure at which gas flow is blocked increases with both foamer solution saturation and with concentration of foamer in solution.

Limited tests suggest that gas flow blocking is much more pronounced in unconsolidated porous media than in consolidated ones, and only slightly pronounced in a fractured sandstone.

An interesting difference exists between beach sand (K=3.6 darcy) and boise sandstone (k = ?) in regard to blocking pressure vs saturation of foamer (see fig 5), with a higher foamer saturation needed (to achieve a given blocking pressure) for the Boise. (my note: this would go along with the relationship discussed by Jimenez and Chambers between perm and foam stability, with the foam being more stable in what is probably the more permeable medium, the sandpack.)

****

Raza S.H., "Foam in Porous Media: Characteristics and Potential Applications" SPEJ page 328 Dec. 1970

It is shown that foam can be generated and propagated in porous media representative of reservoir rocks at pressure levels ranging from atmospheric to 1000 psig, and under pressure differentials ranging from 1.0 to 50 psi/ft. The foam quality depends on the type of foaming agent, concentration, porous medium, pressure level, and the composition and saturation of fluids present. The study shows that flow behavior of foam in a porous medium is a complex one which cannot be correctly described in terms of the high apparent viscosity of foam. Also the concept of relative permeability is not applicable to the flow of foam due to the associative nature of its components.

Unconsolidated sand packs ranging in permeability from 2200 to 39300 md and in naturally consolidated rocks ranging in perm from 1.5 to 1000 md. Microscopic observations of the generation and propagation of foam were made in micro-models constructed of wafers of an artificially consolidated rock. The screening results indicate that the nonionic foaming agents produced high quality foam but the foam films were brittle and unstable. The anionic foaming agents produced low quality foam but the films were gelatinous and stable. Found foam quality independent of concentration when conc. was greater than 0.1 percent, when conc was less than 0.1 percent, then foam quality decreased as conc was decreased.(these quality measurements were essentially an indication of trapped gas saturation, showing that trapped gas saturation(fractional gas –quality produced) increases with increasing surfactant concentration, but stabilized at about 79% above 0.1 wt percent. That is, he looked at gas flowing fraction at breakthrough and equates this with the quality of flowing foam in the medium. Results showed that in homogeneous porous medium the quality of foam generated is a direct function of the absolute permeability, the higher the absolute permeability, the higher the foam quality. No similar correlation was found for nonhomogeneous porous media. In all cases foam quality was drastically reduced when oil was present, with crude oil being more detrimental than refined oil. Attempts to match foam flow with high viscosity oil flow was unsuccesful, leading to the conclusion that the propagation behavior of foam is significantly different from that of a high vis Newtoniam fluid. Found that relative permeability to water at a definite water saturation changes with the change of water flow rate, hence not a single valued function of water satureation. Found improved results by injecting three small slugs of surfactant rather than 1 large slug, and hypothethized that the increasing effectiveness of each successive slug was due to the fact that it reduces the oil saturation, rejuvenates the existing foam, and regenerates foam in pore channels wherein foam collapse has occured.

****

Mast, R.F., "Microscopic Behavior of Foam in Porous Media", SPE 3997 Oct.1972

Foam or gas was injected into etched glass micromodels saturated with a detergent solution, causing some pores to be blocked, and resulting in flow patterns being altered because the resistance to flow differed. With time, foam breakdown, foam drainage, and foam regeneration altered the capillary resistance to displacement along any given flow path. Foam drainage was an important factor in determining foam stability and drainage, and stabiity together with drainage influenced the blocking mechanism. When foam was present, liquid in the foam was held in the large pore openings. The liquid phase could drain from the foam in these pores and saturate the surrounding small pores with liquid. In all the experiments, some liquid and gas were transported as foam, and as the stability of the foam increased, so did the proportion of liquid and gas thus transported through the porous media. Foam stability was increased by increasing the concentration of detergent in the solutions that were used to generate foam. The etched porous network was 2 by 4 inches (glass). Different flow was obtained when the pores were uniform vs not uniform. The detergent Orvus K. was used in all runs. In the non-uniform models: small foam bubbles accumulated in the large pores, the liquid in the pores was continually displaced. As the process continued, the liquid between the bubbles drained away until only thin membranes separtated the bubbles. The reduction in the percentage of liquid saturation in the large pores continued until the gas pressure in those pores equalled the gas displacement pressure of the small pores forming the exit to the large pores. At low conc. of foamer (0.1%) the drained foam membranes were not stable in the large pores, and they broke, leaving a single large bubble, or several large bubbles occupying the large pore. High conc. produced more stable foam, and most could be displaced into the fine pore system.

A good discussion is given, citing Garduscu, of the pressure required to displace a film into a conical restriction, which would be good to add to report.

When foam is unstable, transport of liquid and gas occurs primarily by the progressive breaking and regeneration of the foam structures between large pores that are separated by small pores. No liquid channels were observed, but some of the liquid transport is through the Plateau borders connecting local areas of high liquid saturation, both in the foam and adjacent to the solid surfaces. When foam is stable, the liquid and gas are transported primarily as foam. Some breaking and regeneration occur and the bubble size of the foam is also influenced by foam subdivision. Flow through portions of the porous network is temporarily blocked by the foam. This is equivalent to a reduction of the single phase permeability of the medium. Temporary blocking is the result of the distribution of liquid and gas in the porous system, wettability effects, and the influence of flow rate on surface tension. Foam drainage has a strong influence on foam stability and appears to be an important factor in determining the behavior of foam in porous media.

****

Marsden, S.S., Jr., Elson, T., and Guppy, K., "Literature Review of the Selective Blockage of Fluids in Thermal Recovery Projects" Nov 1977

One of the major problems encountered in thermal recovery projects is the tendency for injected fluids to channel through the higher permeability strata. Thus the lower permeability zones are not exposed to heat and not subject to enhanced oil recovery. Foam can be viewed as a dispersion of gas bubbles in liquid. Small bubbles tend to decrease in size and disappear, while larger ones grow at the same time (ref given). The quality of foam is the volumetric concentration of gas in the foam. For the case where the change of gas solubiltiy in the liquid can be ignored, a simple relationship exists between quality and pressure (ref given). In low quality foams (¡70%) the bubbles are al spherical in shape, while in high quality foams (¿90%) they are multifaceted polyhedrons. An increase in quality of bulk foam seems to lead to an increase in the size of the bubbles rather than just an increase in their number(ref given). Most aqueous foam behave like pseudoplastic fluids with remarkably high apparent viscosity. The apparent viscosity increases with quality. If we consider the flow of liquid and gas foam from the relative permeability standpoint, i.e., as two separate fluids (ref. given), it is found (2 ref given) the relative perm curve for the liquid is about the same as that for a liquid-gas case, but the relative perm curve for the gas is much lower when foam is present.

****

Gopalakrishnan, P., Bories, S.A., and Combarnous M., "An Enhanced Oil Recovery Method: Injection of Steam With Surfactant Solutions", SPE 7109 Feb, 1978

An injection procedure has been defined which makes for, by an alternative injection of surfactant slugs and steam slugs, a significant decrease in the residual oil saturation compared to displacements by steam alone. Injecting using a SAG scheme of 4 small 5% pv slugs gave better results than one large 20 pv slug(porous medium was 120 cm long (47 inches). It also delayed breakthrough slightly longer than a continuous injection scheme.

(not read thoroughly)

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• 1980

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Bernard, G.G., Holm, L.W., Harvey, C.P., "Use of Surfactant to Reduce CO2 Mobility in Oil Displacement", SPEJ August 1980

Determined that surfactant can enhance the production of residual oil from watered out carbonate cores by C02, showed that the permeability reduction caused by surfactant can be dissipated by injection of brine. (Actually quite a few were injected, with most of the removal taking place with 8 to 10 pore volumes, but still some removal of foam was taking place after 22 pore volumes and indicated by the continuing increase in brine permeability.) Found that the efficiency of the presently used WAG process can be increased substantially by adding surfactant to injection water. When WAG CO2/H20 injection is used with surfactant, CO2 mobility is reduced 50% more than if plain WAG is used and considerably less water injection is required. Found mobility reduction to be greatest in oil-free or water-swept sands using Alipal CD-128, which was deemed good since the process is self regulating in that surfactant tends to retard flow where flow rates are greatest and CO2 is not wasted in oil-free zones.

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Mohanty K.K., Davis H.T., and Scriven, L.E., "Physics of Oil Entrapment in Water-Wet Rock", SPE 9406 Sept 1980

Reports the physics of the pore level events of a water flood, and their integration on a square network. Some good discussion is given and many similarities exist between this and foam flow physics. Choke-off is discussed.

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• 1981

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Holcomb, D.L., Callaway, E., and Curry, L.L., "Chemistry, Physical Nature, and Rheology of Aqueous Stimulation Foams", SPEJ Aug 1981

Laboratory equipment was designed to study the microscopic structure of flowing foams at high pressure. Capillary viscosity data for these foams is established and correlated with a video-photomicroscopic study of the flowing foam and their bubble qualities. Found that foam viscosities at high differential pressures and shear rates are quite low. Finds that optimal foaming-agent quantities can be obtained at lower surface tension and lower concentration level using fluorocarbon/hydrocarbon blended surfactant with a neutral ionic character.

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Holbrook, S.T., Patton, J.T., and Hsu, W., "Rheology of Mobility Control Foams", SPE/DOE 9809 April 1981

Using a capillary vicometer (with different capillary sizes) the rheological properties of some promising foams were measured. Data collected at different shear rates show that foams are pseudoplastic in nature and several orders of magnitude more viscous, 10 - 100 cp, than its gas or liquid fraction. Foam viscosity was found to be an inverse function of density, that is the apparent viscostiy increased with foam quality and the quality at which the maximum occured increased when capillary diameter decreased (since less water is needed to stabilize the foam in a small tube as the lamellae size would not need to be large, as compared with a large tube). Also, the apparent viscosity increased with increasing capillary size (this makes sense since for a given bubble size, injection into a larger tube means more lamellae per unit length, and as Hirasaki showed, more resistance.).The flow properties were studied by passing foams through capillary tubes of various sizes and analyzing the shear-stress and shear-rate data. The foams were generated in a porous matrix. The liquid phase consisted of brine containing calcium and an ethoxylated alcohol sulfate. The gaseous phase consisted of nitrogen. The surfactant solution used was 0.5% Alipal CD-128 in a 3% NaCl brine containing 100ppm calcium ion. In the foam generator, the flow was maintained constant to assure constant bubble size. The generator produced uniform foam both in flow rate and in bubble size. The quality of the foam was established by fixing the flow rates of the nitrogen and solution. Photos were taken of the foam to determine the bubble size and size distribution. Evidence indicates that the bubbles deform significantly during flow; and shear-induced coalescence was observed, primarily in preliminary tests employing a surfactant with lower foamability.

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• 1982

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Dilgren, R.E., "The Laboratory Development and Field Testing of Steam/Noncondensible Gas Foams for Mobility Control in Heavy Oil Revoery", SPE 10774 March 1982

Ottawa sand packs of nominal 12 in. length with a diameter of 1.54 inch. Permeabilities were about 4 darcies and porosities of about 34%. The packs were mounted vertically with flow from bottom to top. A Kern River crude oil saturation of about 30% was established and the permeability to steam in the absence of foam was measured. Then water (3ml/min) converted to 50% quality steam plus steam foam components (surfactant, salt, and noncondensible gas) were injected at constant mass rates. The ratio of the permeability to steam vapor in the presence of foam to the permeability to steam vapor in the absence of foam is termed the "permeability reduction factor". This factor is used in the study to indicate foam strength. The smaller the factor, the greater the steam foam strength. Concentrations of surfactant and salt refer to the liquid phase of the foam entering the sand face. Mole fractions of noncondensible gas refer to the gas phase of the foam entering the sand face. Of the two surfactants checked Siponate A-168 and Witco Exp. 4498-43b, neither showed a strong dependence on surfactant conc. , although both did show stronger foams with increases in concentration. The effect of NaCl (0,1,3, and 5 wt%) —with surfactant concentration in the liquid phase of foam entering the sand face being 0.5 wt%, and mole fraction of noncondensible gas (nitrogen) in the gas phase of the foam entering the sand face being 0.0060— was that while each surfactant showed a significant increase in foam strength when salt conc. was increaed from zero to 1 wt%, neither surfactant showed much variation in going from 1 to 5 wt%. Both surfactants salted out of solution when the NaCl concentration is raised to about 6 to 7 wt% at the boiling point of water at atmospheric pressure. The effect of mole fraction on noncondensible gas (holding surfactant conc. 0.5wt% and salinity 3.0wt% constant) over the range of 0.0005 to 0.05 mole fraction showed little change, as long as there was some. That is with 0.0005 the permeability reduction factor was 0.201, and did not decrease with more nitrogen. The effect of steam quality was checked. Most of the runs were at 50% steam quality (0.5 wt % Siponate DS-10, 1.0 wt % NaCl, and 0.006 mole fraction nitrogen) which gave a permeability reduction factor of 0.18. When steam quality was reduced to 20 %, all other experimental variables being equal, the permeability reduction factor decreased to 0.021 relative to 20% quality steam without foam components. A possible reason is that with low quality steam, the mass of surfactant present in a unit of pore volume is greater for the low-quality steam case. The surfactant is present in the liquid phase of the foam, and lower quality affords "wetter" foam, i.e., higher liquid saturations in the porous media. (my note: they did indeed add more mass of surfactant when they used the lower quality! since the liquid phase concentration was constant, but the amount of liquid added in the lower quality case was higher, hence there was no dilution taking place at all). C16 - C18 alpha olefin sodium sulfonates have been shown to be effective, especially with the addition of NaCl and nitrogen. Oil production from the wells comprising the steam foam pilot showed a significant increase in oil production rate over continued steam drive even though the pilot area had been receiving steam continuously for over 10 years. Injection of steam foam significantly increased the pressure at the injection wells.

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Al-Khafaji, A., Wang F., Castanier, L.M. and Brigham W.E., "Steam Surfactant Systems at Reservoir Conditions", SPE 10777 March 1982, paper presented at the 1982 California Regional Meeting, San Francisco, California. (also TR-38)

The following conclusions were drawn concerning Suntech IV, which exhibited high thermal stabiity: 1) CaCl2 caused surfactant degradation at a concentration of 0.5% by weight and greater. 2) NaCl (at 2% by weight and higher) also causes surfactant precipitation and degradation, but below about 2%, no adverse effects are seen. 3) Adsorption was low 4) Phase partitioning to the oil phase is significant, but not linear with surfactant concentration. In addition concerning steam displacement runs: 1) steam mobility was reduced significantly in the presence of surfactant solution, 2) The average steam saturation in the saturated steam zone increased at the steam zone grew.

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• 1984

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Owete S.O, and Brigahm W.E., "Flow of Foams Through Porous Media", Supri TR-37 DOE/SF/115646 (DE 84012410) July 1984

Air was injected into porous micromodels which had previously been filled with an aqueous solution of surfactant. The micromodels consisted of etched silicon wafers anodically bonded to a glass plate, which simulates a monolayer or porous matrix.

The foaming agent used for all the experiments was Suntech IV. The observed mechanism were broadly classified into two: membrane and foam bubble propagation. Propagation of membranes, air-liquid interfaces, occured in the homogeneous porous media at both low and high surfactant concentrations, and in the heterogeneous model at low surfactant concentration. Foam bubble propagation occured only in the heterogeneous model at high surfactant concentrations. (my note: this makes sense with the results of Mast concerning drainage of lamellae films,ie, only large concentrations would resist the high degree of lamellae drainage)

In the homogeneous micromodels, the wetting phase (surfactant solution) formed a continuous liquid network around the matrix, the air was found to progagate as tubular bubbles moving and extending over several pores. The flow mechanism was only slightly affected when different air injection rates, pore dimensions and surfactant concentrations were used. (Interestingly, the Roof criteria cannot be met in Owete's homogeneous micromodel, hence his result of tubular bubbles makes sense).

Foam (bulk?) was found to be generated in the heterogeneous model. Air a liquid were propagated by a combination of channel flow (with liquid confined to small pores) and a bubble "break and reform" process. The break and reform process was caused by snap-off actions at pore constrictions.

A considerable reduction of effective mobility was observed in the presence of foam, compared to air-water systems without surfactant. In both the homogeneous and heterogeneous models, the air mobility decreased with an increase in surfactant concentration. At a specific concentration below the CMC, mobility reduction converged to one value regardless of concentration changes. In the heterogeneous porous medium, surfactant concentration affected the flow mechanism, where the foam bubbles produced with high surfactant concentrations were smaller than those generated in low surfactant concentrations. Bubble size was a function of surfactant concentration, at high conc. small foam bubbles were obtained.

Both spherical and polyhedral foam bubbles were produced. Large bubbles took shapes dictated by pore geometry. Liquid flowed through the small pores while maintaining a continuous network through the foam liquid membranes.

From gas tracer studies (Nahid 1971) the existence of an immobile gas saturation was seen, which increased with increasing conc. of surfactant. The immobile gas sat. ranged from only 4% in the absence of surfactant up to 30% at a surfactant conc. of 1%.

A method is given of measuring CMC

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Al-Khafaji A.A., Castenier, L.M., "Effect of Temperature on Degradation Adsorption and Phase Partitioning of Surfactants Used in Steam Injection For Oil Recovery", Supri TR-38

The aim of the study was to study surfactants for their longevity under conditons typical of those found for steam injection oil recovery, namely at 400 degrees F and 300-500 psia. Adsorption onto sand and clay surfaces and the partitioning of surfactants between water and oil phases were also studied.

Al-Khafaji, A., Wang F., Castanier, L.M. and Brigham W.E., "Steam Surfactant Systems at Reservoir Conditions", SPE 10777 March 1982, paper presented at the 1982 California Regional Meeting, San Francisco, California.

The following conclusions were drawn concerning Suntech IV, which exhibited high thermal stabiity: 1) CaCl2 caused surfactant degradation at a concentration of 0.5% by weight and greater. 2) NaCl (at 2% by weight and higher) also causes surfactant precipitation and degradation, but below about 2%, no adverse effects are seen. 3) Adsorption was low 4) Phase partitioning to the oil phase is significant, but not linear with surfactant concentration. In addition concerning steam displacement runs: 1) steam mobility was reduced significantly in the presence of surfactant solution, 2) The average steam saturation in the saturated steam zone increased at the steam zone grew.

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Marcou, J.A., Brigham W.E., Castanier L.M., Sanyal S.K., Malito O.P. and Strom J., "A Field Experiment of Improfed Steam Drive with InSitu Foaming", Report for DOE September 1984

The surfactant Suntech IV was succesfully injected into a mature steam drive in the Kern River Field of California. The experiment showed that this process could be economically employed on a lease wide basis. Injection pressures quickly rose when small amounts of the surfactant and nitrogen were added to the steam. Injectivity profiles during the first slug indicated that in the near-wellbore region the flow of the steam, and hot water condensed from the steam was diverted to enter new parts of the formation. The diversion of injected fluids did lead to increased oil production rates. After each slug was injected a pronounced increase in oil production was observed in the test pattern. Futhermore, longer slug duration seemed to lead to longer peaks in the oil production.

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• 1985

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Hirasaki, G.J. and Lawson, J.B., "Mechanisms of Foam Flow in Porous Media: Apparent Viscosity in Smooth Capillaries" April 1985

For foam flow through smooth capillaries, the predominant factor affecting apparent foam viscosity is the foam texture (bubble size). Foam of finer texture has more lamellae per unit length and, therefore, a greater resistance to flow. A graph showed a relationship between apparent foam viscosity and bubble radius, with smaller bubbles having the greater viscosity. Beyond a certain bubble size, the "foam" is in large bubbles separated by individual lamellae. Below a certain bubble size, the foam is considered as bulk foam, with the transition between bulk foam and larger bubbles separated by lamellae as being discontinuous. A curve relating capillary radius and apparent viscosity showed that the apparent viscosity is proportional to the capillary radius to the 2.5 power, so larger radius give larger apparent viscosity. (varies to the 2.0 power for bulk foams). The dependence of apparent viscosity on the foam texture for the cases studied is that viscosity is proportional to the -2.0 power of the equivalent bubble radius for bubble radii that are small compared to the capillary radius (bulk foams), and to the -3.0 power of the equivalent bubble radius for bubble radii that are large compared to the capillary radius (lamellae foams), that is, viscosity increases as the bubble size decreases. The dependence of the apparent viscosity on the velocity for the cases studied show that it is proportional to the -1/3 power of velocity when the length of the thin film portion of the bubble is negligible or is very large, that is, viscosity decreases as velocity increases. Apparent vis in smooth capillaries is only one component affecting the mobility of foam in porous media. The apparent viscosity is the sum of three contributions: 1) that from slugs of liquid between bubbles. 2) the resistance due to deformation of the interface of a bubble passing through a capillary , and 3) the surface tension gradient that results when surface active material is swept from the front of a bubble and accumulates at the back of it. Previous observations of flow of foam lamellae in transparent porous media show that the lamellae move from pore to pore by translation. Breaking and re-forming of lamellae was rare, as was bubble coalescence. Measurements and theory presented here show that the most important variable affecting foam viscosity in uniform, smooth capillaries is foam texture(bubble size). Foam of finer texture has more lamellae per unit length and, as a result, greater resistance to flow. This is true both for flow of bulk foam and series of lamellae.

My notes: It is important to remember that when checking the effect of radius on apparent viscosity, they kept the bubble radius, foam quality, and foam velocity fixed. Under such conditions, as fixed bubbles move into larger capillary, there will be more lamellae per unit length, hence a greater pressure drop, so the results make sence. Likewise, for the bubble size effects, they kept the capillary radius, foam quality, and foam velocity fixed. In such a case, it is understandable that as the bubble size decreases for a given capillary size that the apparent viscosity would increase since smaller bubbles mean more lamellae per unit length. Additionally, when checking foam quality effects, they kept capillary radius, gas velocity, and bubble radius fixed. Hence as quality is increased, then there will necessarily be more lamella per unit length (for a fixed capillary size), and therefore the result of increasing apparent viscosity with increasing quality makes sence. Hirasaki, though, say that the real importance of quality increases is to change the radius of curvature of the bubble plateau regions, which is more significant at high qualities. He feels the quality has a lesser effect on the number of lamellae per unit length, the leingth of the thin film portion of the bubbles, and the length of the liquid slugs. These latter effects are more significant at lower qualities he says.

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Robin, M., "Laboratory Work on Foaming Additives to Improve Steam Drive Efficiency" Inst. Franc. du Petrole presented at 3rd European Meeting on Improved Oil Recovery, Rome, Italy, April 16-18, 1985

Discusssion: Concerning the sensitivity of foamimg properties or the foam stability in the presence of a hydrocarbon phase, the following assumptions can be formulatied: This cannot be explained by significant partitioning of the surfactant to the oil phase as analysis carried out by surfactant titration pointed out that the surfactant concentration in the oil phase was always very low. Conventional surfactants consists both of a hydrophilic and an oleophilic part. In the absence of any hydrocarbon phase, and disgrading the mineral phase, the surfactant would tend to migrate toward the water-gas interface. The hydrophilic part will stay in the aqueous phase, while the oleophilic part will penetrate into the gaseous phase. If a hydrocarbon phase is added, the hydrophilic part of the surfactant molecule will remain in the aqueous phase. As for the oleophilic part, the water-gas interface would then compete with the water-oil interface, probably with a preference for the latter, hence a migration of the surfactant molecules from the water-gas interface to the water-gas interface. The result would be a decrease in the surfactant content at the water-gas interface in favor of the water-oil interface, to the extent of preventing foam formation or destroying it.

The solution would then consist in using surfactants such as the substituted ones, the hydrophobic part of which is not oleophilic. Under these conditions, the competition between the water-gas and water-oil interface would no longer occur and this would ensure mechanical foam stability in the presenece of a hydrocarbon phase. Conclusions: foam stability of most surfactants tested were consideraby deteriorated when temperature increased. However, this negative effect can be reduced by increasing the pH, and by using different additives. Increasing hydrophobic chain length seems also to provide foams which are more stable. Foam stability of most surfactants are also affected by the presence of a hydrocarbon phase. This does not seem to be due to a partitioning of the surfactant between the aqueous phase and the hydrocarbon phase, but to surfactant migration from the water-gas interface to the water-oil interface. Using surfactants the hydrophobic part of which is not oleophilic ensures mechanical foam stability in the presence of a hydorcarbon phase. The apparent viscosity is the sum of three contributions: mechanical foam stability in the presence of a hydrocarbon phase.

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Castanier, L.M. and Brigham, W.E., "Selecting Foaming Agents For Steam Injection Improvement", CEP June 1985

Laboratory study focusing on two main objectives: 1) Temperature stability of foaming agents at steam injection conditions and 2) determination of the flow properties of foam in porous media. Conclusions: 1) several surfactants are thermally stable for extended periods of time. 2) adsorption and partitioning into the oil phase are significant and must be studied before any field implementation. 3) salts and divalent ions may cause surfactant precipitation and/or degradation. Concerning flow properties the conclusions were 1) the wetting phase formed a continuous liquid network around the matrix, using a two-D flow, gravity override and channeling of gas was reduced and recovery pmproved by in-situ generation of foam. In situ foaming increased with surfactant concentration until the critical micelle concentration (CMC) was reached. Above the CMC, addition of surfactant had very little effect. History dependent rheology (from Trienan) was observed.

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Treinen, R.J., Brigham, W.E., and Castenier, L.M., "Apparent Viscosity Measurements of Surfactant Foam in Porous Media", Supri TR-48 Oct. 1985

Experiments were conducted in four sand packs, that were saturated with either a surfactant or water solution. Foam of known quality and flow rate was generted from nitrogen and surfactant solution passing through a foam generator. The foam was then passed through a sand pack of known permeability. After a period of time needed to reach steady state conditions, the differential pressure across the pack was recorded, and apparent viscosity calculated using Darcy's law.

Foam quality and surfactant concentration have significant effects on the texture of foam as observed in the observation cells. It must be noted that foam behavior in the cell may not reflect the true behavior in the porous media. For instance the physical size of the bubbles in the observation cell are usually 10 to 15 times larger than the pore spaces of the sandpack. Bubbles smaller than pore size were not seen in the visual cells. One could speculate that bubbles smaller than pore size do not occur in porous media. High surfactant conc. (0.05 to 0.3 wt%) gave foam texture that was independent of concentration. Over this concentration range the following observations were made as foam quality increased. At a quality of 70% bubble size was uniform and approximately 0.010" diameter. Bubble shape was approx. spherical. Increasing foam quality was marked first by distortion of bubble shape, a flattening of the surface where two bubbles touched. When quality reached 90% clusters of small bubbles were present, but the majority of the gas volume was in large bubbles up to 0.07" diameter. These large bubbles tended to be not as large when the flow velocity increased. (My note: this makes sence since the lower quality has less surfactant around, it is reasonable to expect that the exising bubbles will be less stable on their way to the observation glass, and will coalesce to a large degree. However, for increased velocity there will be less time to coalesce and so the bubbles should not be as large). At low conc. (0.005 to 0.01 wt%) increasing foam quality had dramatic effects on foam texture. At a quality of 75% for the 0.005 wt% foam, the foam broke down into a free gas. Owete points out that there is insufficient surfactant in solution to stabilize the foam. Foam apparent viscosity was (as measured by pressure drop across the pack found to increase slowly with foam quality indicating that apparent vis measured in capillary tubes must be compared cautiously with apparent vis measured across a sandpack. Conclusions: a) at low conc. , the apparent viscosity of foam increases sharply with surfactant concentrations. b) At conc. near the CMC apparent vis. of foam becomes independent of surf. conc. c) Increasing flow velocity causes a significant decrease in the apparent viscosity of foam. d) the flow history of surfactant foam in porous media has significant effects on the apparent viscosity of foam.

My note: It is interesing that the make-and-break(MAB) vs the bubble-train-translation (BTT)methods of foam transport will do a good job of explaining Treinens results concerning foam quality. It must be understood, that lowering quality can both increase and decrease apparent viscosity. The explanation is that in the BTT mode, increasing quality increases the lamellae per unit length and increases resistance (as long as this mode can continue!). If this type of transport breaks down into a MAB mode, then increasing quality only serves to further decrease lamellae lifetime and decrease resistance. Since lamella don't transport in the MAB mode, then increasing lamellae per unit length is not the governing factor. It is also possible to have something in between, say 20% by MAB and 80% by BTT. In such cases, the increase or decrease in resistance with quality increase will be less obvious, and may even seem to be independent of foam quality. This goes along very well with Treinen's figure 11, he shows apparent viscosity vs foam quality for various concentrations of surfactant. At low concentration (0.005 wt%) and 70% foam quality, the apparent viscosity is about 22 cp. Then as the quality is increased further, the apparent viscosity actually decreases slighly. This can be understood if we consider that the mode at 70% quality in predominantly the MAB mode. For such a case, any further increase in foam quality will further decrease the fraction of lamellae that can translate by decreasing lamellae lifetime due to increased capillary suction and decreased surfactant mass availability. As the concentration is increased to 0.01 wt%, the apparent viscosity at 70% quality is approx. 36 cp, (increased over the lower conc. case) which is indicative of increased lamellae stability (lifetimes) and an increased fraction of lamella transport by the BTT method. The apparent viscosity does not change over the range of 70 to 80% quality, indicating that the detrimental effects of quality increase on lamellae lifetime is being offset by the increased lamellae per unit length being injected. As the quality is increased further, the destabilizing effects of less surfactant availability(less in solution since we have less solution), and increased capillary suction, push the transport mode strongly toward the MAB mode, and the foam breaks down to a large degree. This,interestingly enough, appears to be an attempt by the porous media to increase the in-situ water saturation by coalescene as per the Khatib results.Now, by increasing conc. still further, (to 0.05 0.15 0.3 wt%) , the apparent viscosity increases to about 56 cp (for all cases), indicative of long lamellae lifetime, and a high degree of BTT. As quality is increased (meaning more lamellae per unit length being injected) then this increased amount of lamella and bubbles that need to be shaped and translated causes and increase in the apparent visocity as the quality is increased. Howerver, since the slope is not large, it indicates that there is still a fair degree of transport by the MAB process (or else it simply indicates that the bubbles are being shaped by the porous medium anyway so there really aren't, except at the inlet, more lamellae per length).In anycase, the increased lamellae per unit length at the inlet say, causes an increase in resistance that is not offset at this stage by any decrease in coalescene time. However, as the quality reaches about 85%, the increase in quality causes a decrease in resistance, indicating that the decrease in surfactant solution and increased capilary suction are decreasing the lamellae lifetime sufficiently (or increaseing the percent transporting via MAB vs BTT) such that the resistance decreases and offsets any increased resistance in the inlet due to more lamellae per unit length. Although he did not go to higher qualities, it is expected that eventually, the higher concentration solution would also have broken down.

By precise regulation of the nitrogen and surfactant flow rates, foam of a desired quality and flow rate was achieved. The sandpack was 1" in diameter and 24 inches in length, which allowed a flow velocity of 2.8 ft/day at a quality of 90%. The sandpacks used had permeabilty ranges from 5 to 8 darcies. Suntech IV was used for all runs. The data on the effects of flow velocity corroborate the non-Newtonian behavoir of foam reported by Raza and Marsden(1965).

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Falls, A.H., Gauglitz, P.A., Hirasaki, G.J., and Miller, D.D., "Development of a Mechanistic Foam Simulator: The Population Balance and Generation by Snap-Off" April 1986

Gives a useful definition of foam inside porous medium as: a dispersion of gas in a liquid such that the liquid phase is continuous (i.e. connected) and at least some part of the gas is made discontinous by thin liquid films called lamellae. This definition encompasses both bulk foams, in which the average bubble size is much smaller than the dimensions of the pore space, and so-called individual lamellae foams, which the bubble size exceeds the pore size. The paper goes on to define two classes of foams. The first is a continuous gas foam, where at least one gas channel exists that is continuous (that is uninterrupted by lamellae) over a macroscopic portion of the sample. Foam lamellae exist, but are stationary and simply prevent gas from flowing through part of the pore network. Thus, gas can flow through the pore network without having to displace lamellae. The other type of foam is called a discontinuous-gas foam. In such foams, all the gas phase is made discontinous by lamellae and there are no gas channels that are continous over large disturbances. For gas to flow, lamellae must be transported through the pore system.

In a water-wet porous medium, the liquid-phase relative mobility does not depend on whether the gas exists as a foam (references Bernard and Holm, and Lawson and Reisberg). Most of the liquid resides either in smaller pores, which do not contain gas, or next to the solid in pores that are occupied by both phases. As long as the amount of liquid carried in lamellae is small compared to the total flux of liquid, the mobility of the liquid can be taken as the usual function of its saturation.

The ways that foam reduces gas mobility can be understood. If a portion of the gas phase is continuous, foam diminishes the cross-sectional area through which gas is able to flow. This may be considered to be a relative permeability effect, the foam creating a large effective trapped-gas saturation. If, however, the gas phase is discontinous, not only can its relative permeability be smaller, but it appears to have a larger viscosity. For gas to flow, lamellae must be forced through the pore network. The apparent viscosity of foam in porous media depends strongly on the texture of the foam (3 papers refe.). The finer the texture, the larger the number of lamellae that must be transported through the system. Unfortunately, texture can also change within a porous media.

So foam texture not only governs foam mobility but can vary within pore spaces. Some mechanisms which alter texture in situ are : capillary snap-off, division, coalescence, and mass transfer between bubbles due to diffusion or condensation and evaporation.

Capilary Snap-off, first described by Roof as a mechanism that traps oil during waterflooding, can generate foam lamellae when the nonwetting phase is a gas(ref given). (my note: remember that surfactant is not needed for bubbles to occur, but only to stabilize the bubbles once formed).

Division, can occur at a fork in a flow path. If stationary lamellae block flow through one brance, lamellae merely flow through the other side. Foam texture is unchanged. That is, the bubble size which exits from the system is the same as that which enters it. However, if the pressure gradient is large enough to mobilize lamellae in both branches simultaneously, lamellae divide. When division occurs, the texture of foam emerging from the system is nonuniform and is finer than that which enters the pore branch, hence the texture has been modified.

Coalescence, the process of lamellae rupture, will certainly decrease bubble density. Stationary amd moving lamellae may rupture by different mechanisms.

Mass Transfer between bubbles can be important as bubble density can change as a result. Because the pressure in a smaller bubble can be greater than that is a larger one, large bubbles can grow at the expense of smaller ones as mass is transferred through lamellae. Pressure-driven diffusion can be a fairly slow process, especially if the gas is realtively insoluble and has a low diffusivity in water. In foams made from condensible gases, such as steam foam, mass can be transferred between bubbles by evaporation and condensation. This change of phase is ordinarily more rapid than diffusion and can quickly destroy foams outside porous media. In fact, steam foams are often formulated with a small amount of noncondensible gas to stabilize them to condensation and evaportation(ref given).

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Falls, A.H., Lawson, J.B. and Hirasaki, G.J., "The Role of Noncondensidble Gas in Steam Foams", SPE 15053 April 1986

Field tests suggest a steam foam drive to be more effective when nitrogen, methane, some other non-condensible gas is added. A plausible explanation is that foam lifetime is longest when transport of noncondensible gas limits mass transfer between steam bubbles. A way to estimate the amount needed is given.

In laboratory studies foams reduce steam mobility up to fortyfold (ref.). That they enhance steam drives has also been demonstrated in several field tests (ref.). By diminishing steam mobility, foam augments the viscous pressure gradient in the reservoir. Heated oil flows more readily, the steam zone expands more rapidly, and volumetric sweep improves (ref.). Sodium Chloride, was used at Shell because it enabled alpha olepfin sufonates to decrease steam mobility (ref). Since then its role in the transport of surfactants through reservoirs has also become known (ref.). Noncondesible gas has been another ingredient of steam foams (ref.). Foams whose vapor phase consists of steam alone can be generated (ref.), but their lifetimes are short (ref.). Consequently, even though a foam can control steam mobility (ref.), improve injection profiles (ref.), and recover additonal oil (ref.), without noncondensible gas, its efficiency is enhanced by including a material having limited solubiltiy in water and a boiling point much lower than that of water. The nc. gas apperars to lengthen bubble lifetime and thus decrease average foam bubble size by suppressing mass transfer due to condensation and evaportaion of water, which quickly destroys steam foams outsid of porous media.

Conclusions: Field tests show that: Even without n.c. gas in the formulation, foams appear to reduce steam mobility, improve injection profiles, and raise reservoir temperature, AT LEAST NEAR INJECTION WELLS. Steam foams made up without n.c. gas have been reported to recover more oil than straight steam drive and lessen the rate of steam being vented at the producers. When n.c. gas is included, bottomhole pressures increase over what can be attained ith a foam of pure steam. If the objective is to increase the pressure gradient across the heated oil (ref.) this enhances the process. Foams formulated with 0.5 mol% Nitrogen reduced steam mobility, raised reservoir temperature, and increased vertical sweep over 100 ft from injectors in Kern River Field. When noncondensible gas is incorportaed, steam foams recover additional oil over a straight stream drive, increase the oil fractional flow at the production wells, and improve oil/steam ratios. Bubbles have a short lifetime when their collapse is limited by transport of heat (condensation/evaportaion) mechanism. At temperatures less than 400 degrees F the lifetimes of steam bubbles in a bulk foam are at least ten times longer when n.c. gas is present in concentrations greater than 0.1 mol percent. The benefit of adding n.c. gas to a bulk steam foam decreases as the temperature increases. The amount of n.c. gas needed to suppress condensation and evaporation of water in a bubble of specified radius diminishes as the temperature increases. The larger the average pore size in a reservoir, the smaller the mole fraction of n.c. gas required to stabilize a steam foam.

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Sharma, M.K., Shah, D.O., Brigham, W.E., "Effect of Mixed-Chain-Length Surfactants on Fluid Displacement in Porous Media by In-Situ Foaming Process", SPE Res. Eng. May 1986

Maximum foaming, minimum bubble size, minimum surfacte tension, maximum surface viscosity, maximum breakthrough time, and maximum fluid displacement efficiency were observed when the two components of the surfactant system had the same chain length. The micorscopic studies revealed that the order of bubble size measured outside the porous medium for various mixed surfactants was maintained in a micromodel.

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Nikolov, A.D., Wasan, D.T., Huang, D.W., and Edwards, D.A., "The Effect of Oil on Foam Stability: Mechanisms and Implications for Oil", SPE 15443 October 1986

Foam stability in the presence of Salem crude oil and pure hydrocarbons is investigated as a function of chain length of alpha olefin sulfonates and electrolyte concentration.

During the process of three phase foam thinning, three distinct films may occur: foam films (water film between air bubbles), emulsion films (water between oil droplets) and pseudoemulsion films (water film between air and oil droplets).

The interactions between an oil phase and foam lamellae are extremely complex. Foam destabilization in the presence of oil may not be a simple matter of oil droplets spreading upon foam film surfaces but may often involve the migration of emulsified oil droplets from the foam film lamellae into the Plateau borders where critical factors, such as the magnitude of the Marangoni effect in the pseudo-emulsion film, the pseudoemulsion film tension, the droplet size and number of droplets may all contribute to destabilizing or stabilizing the three phase foam structure.

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Bolsman, T.A.B.M., Daane, G.J.R., "Effect of Surfactant Structure on Phase Behavior of Alkylxylenesulfonate/Crude-Oil/Brine Systems", SPE Res. Eng. Jan 1986 p 53

The performance of linear alkyl-o-xylenesulfonates (Enordet LXS) with equivalent weights ranging from 345 to 472 with well-defined molecular structure.

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Duerksen, J.H., "Laboratory Study of Foaming Surfactants as Steam-Diverting Additives", SPE Res Eng Jan. 1986 p 44

The objectives of the laboratory study were to develop a steam-foam surfactant for field testing and to elucidate the mechanisms of steam foam EOR. More than 50 commercial and experimental surfactants were screened for foamability; some were also screened for thermal stability at steamflood conditions. Results showed that: many sulfonate surfactants have good thermal stability; foam requires constant regeneration to be effective; foamability varies inversely with temperature and directly with gas-phase nitrogen concentration; foamability is adversely affected by brine but is relatively insensitive to foam liquid volume fraction; and effective foam can be generated at reservoir flow rates (gas phase velocities of 0.15 ft/min which corresponds roughly to reservoir steam velocity 50 ft. from the injector with a 10 ft thich steam zone and 500 B/D injection of 60% quality steam at 400 F).

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Marsden, S.S., "Foams in Porous Media", Supri TR 49, May 1986

This is a chronological survey showing the development of foam flow, starting with laboratory studies and eventually getting into field tests and demonstrations.

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Friedmann, F., "Surfactant and Polymer Losses During Flow Through Porous Media", SPE Res. Eng. May 1986 p 261

Experimental methods are presented to evaluate and to measure the major contributions to surfactant and polymer losses in Berea sandstone for various oil saturations (no oil to postwaterflood residual oil)

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Sanchez, J.M., Schechter, R.S., and Monsalve A., "The Effect of Trace Quantities of Surfactant on Nitrogen/Water Relative Permeabilities", SPE 15446 Oct. 1986

This paper proposes a single capillary model incorporating the mechanisms of foam generation, propagation, and rupture. The model is a steady-state one. Systematic steady-state experiments are reported to demonstrate two important model predictions. The first shows the remakable effect of even very small surfactant concentrations on the relative permeability to gas and the second set of experiments is designed to verify the model prediction that the relative permeability to gas at a fixed liquid saturation may increase or decrease with increasing liquid rates, both of which have been reported in the literature.

A number of studies have been conducted in porous media and the following (according to the author) may be accepted : 1) When both gas and liquid flow concurrently at a given saturation, the liquid flows primarily through the same paths irrespective of the concentration of surfactant.(ref) 2) A certain fraction of the gas is trapped and does not participate in the flow process. (ref) and 3) The mobile gas moves via a network of bubbles separated by liquid lamellae. These are formed and break at regular intervals (ref). However, apart from these qualitative observations there is still much which is unsettled, poorly understood, or even contradictory. The present work presents a theoretical analysis of lamellae generation and propation in a single toroidally constricted capillary tube. It is shown here that on the basis of the single capillary model, one can understand the underlying mechanisms contributing to some of the seemingly contradictory results.

Once a lamella has formed at the throat, it is not immediately displaced. After a lamella first bridges, the pressure behind must build until displacement of the lamella occurs. The time necessary for the displacement is defined as the growth time.

Their results show liquid relative permeability as being unaffected by surfactant in solution, ie a single valued function of water saturation. CONCLUSIONS: 1) For steady, simultaneous flow of gas and water, theoretical and experimental evidence has shown that only trace quantities of surfactant are necessary to stabilize the flow of gas through water-wet porous media. 2) An apparent drainage-imbibition relative permeability hysteresis exists in the data due to lifetime effects of transient lamellae generated during the initial dynamic displacement. 3) Gas relative perme. is a function of the liquid flow rate through the changes in the Darcy pressure drop. Theoretical analysis shows that as the length of a capillary is increased (ie as the pressure drop is increased) lamellae generaton increases until rupture in the throat occurs. For a distribution of pore sizes one would expect first a decrease and then an increase in gas relative perm as the liquid flow rate increases. 4) At higher gas rates, a lamellae may rupture as it is displaced from the throat due to an insufficient volume to maintain itself in the capillary.

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Wang, F.P. and Brigham, W.E., "A Study of Heat Transfer During Steam Injection and Effect of Surfactants on Steam Mobility Reduction", Supri tr-55 Oct. 1986

The effectiveness of foam on mobility reduction is a function of type of surfactant, surfactant concentration, foam quality, flow rate and absolute permeability. Gopalakrishnan et. al (1978) studied both the interfacial phenomenon of a surfactant and refined oil system and oil recovery by steam displacement with surfactant. They used alternating injections of steam and slugs of surfactant solutions. Their results showed that four 0.05 pore volume slugs of surfactant solution yielded higher oil recovery than a single 0.2 pore volume slug. Surfactant: Suntech IV, Oil: Kadol . Experiments were divided into two major types: a) one slug of surfactant was injected into an oil saturated sandpack at irreducible water saturation; b) alternating slugs of surfactant and steam were injected after the sandpack had been steamflooded and produced to a steam-out condition where no more oil was being produced. The first type was to study oil recovery. The second type was to study steam-mobilty reduction. For the mobility reduction runs, three or more slugs of surfactant solution were injected in each run. The concentration of the surfactant solutions ranged from 0.08 t 1.12 active wt%. Slug sizes varied from 0.05 to 0.30 pore volumes. Nitrogen effects were also investigated, with concentrations varying from 0 to 2.1 mole percent of steam injected. Experimental data showed the steam mobility can be reduced by injecting alternate slugs of Suntech IV (alteranating with steam). The reduction was a function of backpressure, surfactant concentration, size and number of surfactant slugs, and nitrogen fraction in the injected steam. Two or more slugs of 0.1 pore volume or larger were required to achieve the maximum steam mobility reduction of three to four fold. The addtion of nitrogen in the injected steam furthere reduced the steam mibility to about five fold and little effect was seen at nitrogen concentrations above about one mole percent. Thus with the addition of nitrogen at surfactant concentration of 0.2 wt%, the mobility reduction was as large or greater than that found with 1.0 wt% surfactant without nitrogen. *** This paper bears further reading ***

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• 1987

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Demiral, M.R.B. and Okandan, E., "Experimental Analysis of Steam Foam Injection to Heavy Oil Limestone Reservoirs", March 1987

The application of steam foam injection process to Bat Raman heavy oil reservoir of Turkey was investigated by running a series of laboratory experiments. Continuous steam injection was applied to a heavy oil and water saturated carbonate model with the selected surfactant at different slug sizes to investigate their ability in decreasing steam override. During these experiments steam front profile was modified after creating foam in-situ in the model and as a result, up to 45.6% incremental oil was recovered compared to a continuous injection test. The most efficient slug size was found to be 0.17 pore volume when the foaming solution had 1.0% weight concentration. The surfactants used were Enordet AOS and Enordet LTS. conclusions: In-situ foaming during steam foam injection tests modified steam profiles and thus helped to decrease the steam override.

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Demiral, M.R.B. and Okandan, E.,"Steam Foam Injection in a 3-D Laboratory Model"

Study to investigate the use of in-situ foam and steam in calcereous formations, using a 3-D model. The optimum slug size was 0.12 PV at 1.0% .

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Jensen, J.A., Friedmann, F., "Physical and Chemical Effects of an Oil Phase on the Propagation of Foam in Porous Media", SPE 16375 April 1987

Laboratory experiments were performed to determine the effects of a residual oil phase to hot nitrogen flood on the propagation of surfactrant foam in Berea sandstone rocks. Surfactant partioning into the oil phase and thermal degradation losses were measured. Four crude and two synthetic oils were used. The effeect of the presence of an oil phase on foam propagation was found to be strongly surfactant specific. Conclusions: Experiments showed that the oil must be displaced below 15% residual oil saturation before oil-sensitive foam could propagate. The pressure drop due to foam across a sandpack increased as the injected steam quality decreased for the steam-foam test. (steam mass flow rate was 1200 g/min cwe). (my note: the surfactant concentration was kept constant at 1 wt% of STEAM LIQUID PHASE! this is important since it means that the mass of surfactant injected was higher as the quality of steam was lower since the volume of liquid increased. Also the surfactant was injected continuously into the liquid portion of the steam).

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Maneffa, M.G., "A Laboratory Study of Surfactants as Foam Diverting Agents", MS Report at Stanford, June1987

Using the same model as Wang, Hamida, Demiral, and myself, under the same basic conditions but with ROS of 19%, the following was concluded: 1) In general, the SD1000 slugs at concentrations from 0.1 wt% to 1.0 wt% performed no better than the water slugs. This was observed whether or not nitrogen was injected continuously at 5 mole%. 2) The largest pressure gradient increases were observed in the last section of the sandpack for RUN SET III. In this run set, nitrogen was injected at 5 mole % and the last sections for all the SD1000 slugs showed a 10% improvement in the pressure gradient as compared to the base case of water plus nitrogen. 3) For each run in RUN SET III, the second SD1000 slug performed better that the base case of water, and the first and third SD1000 slugs at concentrations from 0.1 wt% to 1.0 wt%. However, the increase in pressure gradients for these second slugs within the sandpack were not significant.

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• 1988

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Yang, C-Z., Huang, Y-H, and Han, D-K, "Analysis and Explanation to Industrial Pilot Foam-Flooding Results on the Lao Jun Miao Field in China", SPE/DOE 17387 April 1988

This paper describes the industrial pilot results of foam flooding for enhanced oil recovery. The pilot operation involved 18 production wells and 8 injection wells. A response was obtained from a small number of the production wells, but no response was obtained from the other wells evem two years later. In principal it was found that the foam was no longer formed farther than 10 meters from the injection well.

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Rossen, W.R., "Theories of Foam Mobilization Pressure Gradient", SPE/DOE 17358 April 1988

This paper presents theoretical models to predict the magnitude of the minimum pressure gradient to mobilize foam in two cases. In the first case, foam lamallae form by snap-off at pore throats during simultaneous flow of liquid and gas through the pore space. Percolation theory relates the minimum pressure gradient to the fraction of pore throats blocked by lamellae, the geo metry of the pore throats , and the topology of the pore network. This theory inciates that in field application foam can begin to flow only at the relatively high gradient found near the well. Effective reservoir sweep with foam therefore depends on the propagtion of foam formed near the well.

In the second case a well-established foam flows as "bubble trains", through regions of trapped gas. Theory predicts that fine-textured foams then have subtantial minimum pressure gradients of tens of psi/ft. If the reservoir gradient cannot sustain the minimum gradient needed, flow stops and the foam plugs the zone. Some coalescense is then needed to avoid plugging and allow foam propagation deep into the formation. Foams canot propagate at field pressure gradients of 1 to 2 psi/ft unless foam bubbles grow to lengths of up to 1cm or hundreds of pores. For succesful foam propagation, foam texture must maintain a delicate balance between formation plugging and foam collapse.

Conclusions: 1) Both the minimum required pressure gradient and the consequences of failing to mobilize the foam depend on the fraction of pore throats blocked by snap-off. If few throats are blocked, gas flows around these blockages as a continuous phase and gas-flow resistance factor is low. However, if nearly all throats are blocked by snap-off, then all gas is trapped gas and resistance factor is infinite unless the lamellae are mobilized. 2) The fraction of throats blocked by snap-ff depends on capillary pressure. Percolation theory suggests that initial foam mobilization by field pressure gradients of 1 to 2 pis/ft is possible only over a narrow range in capillary pressure, which controls the fraction of throats blocked. The range in which foam is mobilized is much broader at the high pressure gradients found near an injection well. Thus initial foam mobilization is likely only near the injection well, where the pressure gradients are high. Sweep of the entire formation by foam therefore depends on propagation of the foam formed near the well. 3) The fraction of throats that must be blocked to form an effective foam depends on the gas saturation when surfactant is introduced into the liquid phase. If the initial gas saturation is relatively low, the gas-occupied network is tortuous even before snap-off begins, and foam formation is easier. If the initial gas saturation is relatively high, then more throats must be blocked to increase resistance to gas flow.

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Friedmann, F., Chen, W.H., and Gauglitz, P.A., "Experimental and Simulation Study of High-Temperature Foam Displacement in Porous Media", SPE/DOE 17357 April 1988

Bubble coalescence is insignificant in short-core laboratory floods when foam residence time is short. Foam generation by snap-off creates moving bubbles above a critical gas velocity which was experimentally determined. The critical velocity (is gas velocity is below this no snap off occured) was determined to be a function of the injected liquid volume fraction, with the critical velocity going to zero as LVF approached 1. That is, as more liquid is flowing through the pores, the gas must displace liquid from a pore or neck, but at low injected LVF, the gas is more connected, so the velocity (pressure gradient) required to invade a (new) liquid filled pore is higher.

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Isaacs, E.E., McCarthy, F.C., Maunder, J.D., "Investigation of Foam Stability in Porous Media at Elevated Temperatures", SPE Res.Eng. May 1988

The paper describes a laboratory study of the factors controlling the formation and breakdown of foams in porous media at elevated temperatures. The degradation of a foam when gas injection was discontinued involved the gradual transformation of a foam with a noncondensable gas phase (gas foam) to a foam with steam as the gas phase (steam foam). The ability to prevent release of the NC gas phase was strongly influenced by surfactant type and concentration. The formation of steam foams in the absence of NC gas was a critical function of steam velocity and permeabilty. Surfactant concentration and chain length, salinity, and the presence of oil were important variable in determining mobility reduction of steam. Increased oil recovery from cores undergoing steam displacement was obtained when surfactant slugs were injected with and without noncondensible gas. The presence of a noncondensable gas led to the formation of a more effective and durable foam.

The absolute permeability of the pack was measured at a number of water flow rates before and after each experiment to indicate when the pack had to be renewed because of silica dissolution at test temperature. Concerning the steam foam run made in 12 darcy sandpack, no changes were apparent until about 2.1 hours, after about 3 pv of surfactant had been injected, when a sudden and dramatic increase in delta p from about 29 to 116 psi was observed. States that CMC increases with temperature and references another author.

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Ransohoff, T.C., and Radke, C.J., "Mechanisms of Foam Generation in Glass Bead Packs", SPE Res. Eng. May 1988

The fundamental, pore level mechanisms of foam generation are investigated in monodisperse bead packs. First, direct visual observations identify the following geration mechanisms: lamella leave behind, gas-bubble snap-off, and lamella division. Then, to ascertain the relative importance of these mechanisms, quantititive experments are pursued on the role of bead-pack permeability (bead sizes from 0.25 to 1mm), gas phase velocity (0.001 t 0.8 cm/s), gas phase fractional flow (0.6 to 1.0), permeability variations, and surfactant type SDBS, SD1000, Suntech IV. We discover a critical velocity above which a "strong" foam is generated and below which only "weak" foam is formed. The snap-off mechanism is the primary mechanism responsible for the formation of the strong foam. A simple model, based of the concept of a "germaination site", is develped to predict the onset of snap-off at higher gas velocities.

At velocities below about 0.2 cm/s , large bubbles with an average diameter of 2mm exit from the bead pack. Closer inspection reveals that these bubbles are in fact generated by the snap off mechanism very near the exit; no motion or indication of bubble production within the bead pack is evident. This result proves that observation of foam bubbles emerging out the end of a porous medium does not ensure that there are foam bubbles inside. It is possible that the bubbles are generated only at the exit. At gas velocities above about 0.2 cm/s very small bubbles are generated near the inlet to the pack. These bubbles after generation near the inlet, flow through the pack in a chaotic and wave like fashion, and with the exception of a few very large bubbles, they appear fairly monodisperse.

Leave behind; As gas invades a previously liquid-saturated region, it percolates through the many interconnected flow channels. Often, two gas fronts approach the same liquid-filled pore space from different directions. When this happens, the liquid in the pore space is squeezed into a lamella by the two fronts. We find a moderate increase in resistance to gas flow as a result of this mechanism. So we say it generates a weak foam.

Snap off: Snap-off creates a separte bubble, putting some of the gas into discontinous form. In addition, it can occur repeatedly at one site. The resistance go gas flowing in bubble or discontinous form through the media is much greater, with apparent viscosities of 100 cp (ref.) Snap was observed at higher injection rates.

Lamella Division: was seen to be more important at higher gas velocities.

Looking at Owete's work, they say that no snap off of gas bubbles was seen in experiments done on the homogeneous model. Only the leave-behind mechanism was observed.

Effect of permeability variations: Snap off is observed at all velocities at the low/high permeability change boundary (ie. as gas flows from a low to a high permeability region). However, no snap off is observed below the critical capillary number at the high/low permeability change boundary.

An interesting result arises from the geometric calculations done (looking at pore body pore throat sizes depending on packing), which is that in the one-layer homogeneous bead pack that exhibits only 1D and 2D close-packing arrangements, the Roof critierion for snap-off cannot be met (my note: this would explain why Owete did not see snap-off in his homogeneous micromodel.

As can be seen from fig 16, there is not probability of snap-ff in the larger pore constriction. They are never conncected to large enough pore bodies to meet the Roof criteria. Conversely, there is a very high probability of snap-ff in the smaller throats. Thus, germination sites tend to be the smaller pore throats.

Using the germination-site concept, the results of the permeability increase experements can be explained. In these experements, snap-off was observed at all velocities at the permeabilty increase boundary. At this boundary there are many small constrictions in the low permeability region that are connected to large bodies in the high permeability region. So, nearly every flow channel leads to a germination site at the boundary, and snap-off is expected at all velocities. This is the same phenomena as teh "exit" foam observed in the visual experiments.

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Jimenez, A.I., and Radke, C.J., "Dynamic Stability of Foam Lamellae Flowing Through a Peroidically Constricted", ACS Symposium Series, June 1988

The stability threshold or critical capillary pressure of foam flowing in porous media depends on the flow rate with higher velocties breaking the foam. As lamellae is stretched and squeezed by the pore wall, wetting liquid from surrounding pores fills or drains the moving film depending on the difference between the conjoining/disjoining pressure and the porous-medium capillary pressure. The interplay between stretching/squeezing and draining/filling ascertains the critical velocity at which the film breaks in a given porous medium of fixed wetting-liquid saturation. Lamellae longevity in porous media is dominated by the meam capillary pressure difference between the nonwetting foam phase and continous wetting aqueous phase.

A very interesting experiment where foam was injected into a dry core and a wet core showed the need for a wetting phase saturation to be above a certain level. Once about 1pore volume of foam had been injected, the profile for the initially dry case approached the initially wet case (This could also be used a an example to push my idea of surfactant concentration, since both cases take a few pore volumes to reach a stabilized pressure drop.). The purpose of this paper was to explain quantitatively the origin of the critical capillary pressure for foam existence on porous media. First the static case is addressed and then the dynamic case. A hydrodynamic theory is introduced to explain how Pc depends on velocity by analyzing the stability of foam lamellae moving through a periodically constricted sinusoidal pore. Inside the lamellae, there is an excess force or conjoining/disjoining pressure, PI, as introduced and tested experimentally by Derjaguin et. al (1939, 1957). This pressure is a function of the film thickness. The typical isotherm shown does not have the short range molecular contributions that are thought to be of structural origin (ref 1987), since it is postulated that these ultrathin films are unlikely to be stable in porous media. The particularcase shown is calculated from the constant and low surface potential subcase of the DLVO theory (Derjaguin-Landau-Verwey-Overbeek). An equation is given for the isotherm which is made up of two term. The first reflects attractive dispersion forces , the second corresponds to repulsive electrostatic double-layer forces. The driving force for exchange of fluid into and out of the film is Pc-PI. When Pc is greater than PI, the pressure difference (Pc - PI) drives liquid out of the lamella and vice versa. If Pc=PI then an equilibriium metastable film is possible. Whether a particular intersection of Pc and PI yields a metastable or an unstable foam film depends on the specific shape of the conjoining/disjoining curve. For a nonthinning unbounded film Vrij (1966) showed via a thermodynamic analysis (surface energy minimization) that when d(PI)/dh is gt zero the film is unstable.

The origin of a critical capillary pressure can be explained. For strongly water-wet media, the aqueous phase is everywhere contiguous via liquid films and channels. So the local capillary pressure exerted at the Platteau borders of the foam lamellae is approximately equal to the mean capillary pressure of the medium. For a static foam, a critical capillary pressure at Pc=Pi demarks the boundary between metastable and unstable foam lamellae. In a given medium at a fixed water saturation, static foam stability depends solely on the value of PI(max). If Pc is greater than PI(max) then the foam will break. PI(max) in turn is determined by the surfactant formulation, since the shape of the conj/disj pressure isotherm reflects the surfactant charge, size, and concentration as well as background ionic strength and hardness. Since in general, lower permeability media exhibit higher capillary pressure suction, the authors argue that it should be more difficult to stabilize foam when the permeability is low, indeed the concept of a critical capillary pressure for foam lingevity can be translated into a critical permeability through use on the universal Leverett capillary pressure

J function and the constatn charge model (eqn given). The expected result is that lower water saturations require more permeable medium for stability. With a simple constant-charge electrostatic model, there is also a strikingly strong dependence of the critical permeability on the ionic concentration. At low salt concentrations, foam can survive in low permeability media. We conclude that the stability of static foam in porous media depends on the medium permeability and wetting phase saturation (i.e. through the capillary pressure) in addition to the surfactant formulation.

For a finite flow velocity both the stretching and squeezing and the drainage-filling rates play important roles. Higher capillary numbers (higher velocities) demand lower critical capillary pressures for metastability or equivalently, higher water saturations in the porous media. The reason is that capillary pumping into the lamella is required to stabilize the film against rupture due to the pore-wall stretching. Lower capillary pressures are necessary the higher velocity because of the finite fluid resistance. At very high capillary numbers, all curves eventually result in a zero Pc(max). This means that a completely water-saturated medium would be required to support the foam lamellae. We also see that large pore-body to pore-throat radii ratios lead to a more unstable foam, which is more dramatic for high capillary numbers. Note capillary number=const*vis*flowrate

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Ginley, G.M. and Radke C.J., "The Influence of Soluble Surfactants on the Flow of Long Bubbles Through a Cylindrical Capillary" June 1988 ACS symp.

Flow of trains of surfactant laden gas bubbles through capillaries is an important ingredient of foam transport in porous media. To understand the role of surfactants, a regular perturbation expansion is presented. Numerous visual micromodel studies of foam generated and shaped in oil-free, water wet porous media with robost stabilizing surfactants, show that the bubble size is variable but generally is on the order of one to several pore body volumes, (ref Ransohoff and Radke, Mast, Hirasaki, Owete, Kuhlum, Huh, Manlowe).

A regular perturbation expansion in large adsorption rates is constructed about the low capillary number singular perturbation theory of Bretherton. The pressure drop across the bubble increases upon the addition of surfactant, whereas the thin film thickness decreases slightly. Both the pressure drop and the thin film thickness retain their 2/3 power dependence on the capillary number found by Bretherton for surfactant free bubbles.

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Khatib, Z.I., Hirasaki, G.J., and Falls, A.H., "Effects of Capillary Pressure on Coalescence and Phase Mobilities in Foams Flowing Through Porous Media", SPE Res. Eng. August 1988

The stability of foam lamellae is limited by capillary pressure. Consequently, as the fractional flow of gas in a foam is raised at a fixed gas velocity, the capillary pressure in a porous medium at first increases and then approaches a characteristic value, here called the "limiting capillary pressure". If the gas fractional flow is increased after the limiting capillary pressure has been attained, coalescence coarsens foam texture, the liquid saturation remains constant(i don't buy it that the saturation remains constant, it would seem necessary that the water saturation increases, at least locally, during coalescence, since the liquid film that broke needs to redistribute itself on the sand grains, hence increasing the saturation and allowing for a foam to be stabilized by dropping the capillary pressure), and the relative gas mobility becomes proportional to the ratio of gas to liquid fractional flow. The limiting capillary pressure varies with the surfactant formulation, gas velocity, and permeability of the medium. The authors hypothethise that 1) the rate of coalescence of foam bubbles in porous media depends on capillary pressure and 2) lamellae in porous media cannot withstand capillary pressures above a limiting value. Experiments confirm that capillary pressure does indeed play a major role in determining coalescence and phase mobilities of foams in porous media. Discussing DLVO theory, the authors discuss literature and experimental evidence for the importance of capillary pressure in foam stability outside of porous media. A previous author is cited that found bulk foams breaking at lower capillary pressures than single films created from the same surfactant solution. They then extend the idea to porous media. They feel that in porous media, the capillary pressure increases up to a limitng capilary pressure as the gas fractional flow is raised. With further increase in gas fractional flow, the capillary pressure remains at its limiting value while the foam texture becomes coarser. The texture must coarsen to keep the capillary pressure from rising above the limiting value. (again, i don't buy their argument, and in fact, their data shows the capillary pressure dropping during coalescence, indicationg that the water satureation is indeed dropping as a result. Also they never measured the pack saturation, but only fractional flow).

The porous media consists of sand or bead packed into either acrylic or glass tubing. Wire screen was used to retain the sand or beads. The surfactants used were 1 wt% Siponate DS-10 and 0.5 wt% Enordet AOS 1618 in 1wt% NaCl. The gas was Nitrogen. No oil was present, and all experiments were at room temp. The Foam was pregenerated. Texture was observed (at oulet of pack) by viewing effluent through a capillary tube(Why? it has been shown by other researchers that an effluent texture does not need to correspond to the in-situ texture, although they did note a change in the effleunt texture–it became much coarser– following an abrupt drop in cap. press. associated with coalescence).

In comparing their measured cap. pressures with those measured by other researchers outside of porous media, they note that their values correspond to bulk foams. The relationship between capillary pressure, foam texture, and the gas fractional flow observed in this study is consistent with the observations and models of foam in smooth cpaillaries. The relationships for a smooth capillary described by Hirasaki and Lawson, apply if 1) capillary pressure is described by the radii of curvature of the plateau borders of lamellae 2)foam texture corresponds to bubble radius, and 3) the gas fractional flow corresponds to quality. (this would imply that once the bubbles had coarsened enough to be the size of the pore bodies, then the limit would be reached, and little coarsening would be possible to reduce the capillary pressure. This would correspond to their figure 6 where a maximum is reached in the critical capillary pressure curve vs gas fractional flow.)

Gas Mobility: Relative gas mobilities for the Siponate DS-10 foams vs the ration of the gas/liquid fractional flow for three gas flow rates shows two straight lines. At low values of gas fractional flow, the relative gas mobility is nearly constant, appearing to decrease slightly with gas fractional flow. Our interpretation of this regime is that the foam texture remains nearly constant, corresponding to what was pregenerated. The small change in the gas mobility is therefore akin to that observed for smooth capillaries (Hirasaki and Lawson) when the gas fractional flow is changed while bubble size is held constant. The second straight line that has increasing relative mobility of gas with increasing gas flow fraction is interpreted as a case where the capillary pressure has reached its limiting value, and so coalescence coarsens the foam. The coarsening of foam texture with gas fractional flow results in the increase in gas mobility.

They found a decrease in the limiting capillary pressure with increase in permeability. They interpreted this to mean that increased perm. would have a destabilizing effect on foam.

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Lau, H.C. and O'Brien, S.M., "Effects of Spreading and Nonspreading Oils on Foam Propagation Through Porous Media", SPE Res. Eng. August 1988

Experiments show that a spreading oil increases the time for foam generation and decreases the speed of foam propagation in a porous media. It also breaks a foam faster than a nonspreading oil. Separate static foam height experiments confirm that a spreading oil breaks foam faster than a nonspreading oil.

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Michaels, K.F. and Udell, K.S., "Foam Production During Steam Displacement of Aqueous Surfactants", SPE Res Eng. August 1988

Conclusions: 1)The presence of a noncondensable gas in the sandpack at any value of saturation does not change the condensation-front velocity, the pressure gradients in the steam zone, or the irreducible water saturation IF NO surfactants are present. 2) The mobility of the steam phase decreases by a factor of 5.7 when the sandpack is initially saturated with surfactant solution, compared with distilled water. Similarly, a decrease by a factor of 14 results when the pack contains both surfactant and noncondensable gas. Hence, even though the NC gas was not injected, it still played a part in stabilizing the foam.

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Manlowe, D.J. and Radke, C.J., "A Pore Level Investigation of Foam/Oil Interactions in Porous Media" SPE 18069 October 1988

They find that the overall stabilityof foam in contact with residual oil in porous media is controlled by the stability of the liquid films separating individual foam bubbles and trapped oil blobs. This film is coined a pseudoemulsion film. If a foam bubble is in contact with an oil blob for a long enough time that the pseudoemulsion film ruptures, foam lamellae surrounding the breakage event collapse. Thus if the pseudoemulsion films generated during flow though porous media are stable, the foam is stable. They assert that the surfactant design should concentrate on stabilizing the pseudoemulsion films.

The experiments made use of micromodels. The oil, which was initially in the form of trapped blobs on the size of pore bodies, was oduced by three modes: 1) foam bubble breakage induced emulsification of oil droplets whose size, compared to the pore sizes, permits flow out of th medium, 2) oil films or lenses form on the borders of foam bubbles and travel with them out of the medium and 3) once a substantial pressure drop is established, large, whole oil blobs are dislodged and produced. Mode 1 dominates at the outset of the foam flood, while mode 3 dominates in the latter stages. The foam reduces the oil saturation in the model from 30% down to approx. 20%. Visual observations of the model after a complete foam flood reveal that the remaining oil exists in trapped blobs whose sizes become on the order of the intermediate to smaller pore bodies.

Results show that a nonspreading hexane destabilized foam to a greater extent than the spreading dodecane. This contradicts the oil-spreading mechainism which would suggest the opposite. Hence the results cast doubt upon the generality of the oil-spreading mechanism of foam breakage in porous media.

After reviewing the accumulated lab data in the micromodels, the foam present in the micromodel remained stable to collapse when the pseudoemulsion films (water films between oil and gas) formed in the medium remained stable and vice versa. The stability of the pseudoemulsion films controlled the stability of the foam, regardless of the subsquent spreading characteristics of the oil. For this system, the type of oil, speading or nonspreading, had no effect on the foam-breakage process. They relate this to capillary pressure suction. Other suggested destabilizing mechanisms by previous authors: 1) Oil (and/or rock) scanvenges surfactant from the gas-water interface 2) Formation of oil-water macroemulsions deplete surfactant from the gas-water interface. 3) Polar components in the oil preferentially adsorb at the gas-water interface displacing or inactivating the more strongly stabilizing surfactant. 4) Oil causes the water-wet rock to become oil-wet which destabilizes the foam. 5) Oil blocks the formation of foam by residing in the germination sites 6) Oil disrupts the orderly stabilizing arrangement of micelles within the foam lamellae. 7) Oil spreads at the gas-water interface inducing lamella thinning and or decreasing the critical capillary suction pressure for rupture.

Number 7 is disproved in this paper. Arguments given against the other mechanisma are as follows. Numbers 1 and 3 are deemed not general enough since–even for nonpolar oils and for surfactant pre-equilibrated oil, water, and rock–foam still breaks. The generality of Numbers 2 and 4 are rejected since oil destabilizes foam in systems that are strongly water wet and in systems that do not form strong macroemulsions. Number 5 is rejected since even when foam in generated outside of the porous medium and injected premade, oil still destabilizes it. Number 6 is rejected since oil destabilizes foam at surfactant concentrations below CMC.

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Lau, H.C., and O'Brien, S.M., "Surfactant Transport Through Porous Media in Steam-Foam Processes", SPE Res. Eng. November 1988

Experimental and theoretical studies show that the transport of steam-foam surfactants through reservoir sands can be substantially retarded as a result of cation exchange between the surfactant solution and the formation clays. Results however show that a high injected salinity favors surfactant propagation by displacing divalent cations faster and by reducing partitioning when divalent cations are present.

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Farrel, J. and Marsden, S.S. Jr. "Foam and Emulsion Effects on Gas Driven Oil Recovery", Supri TR 62 Nov. 1988

The main conclusion is that combining foam and emulsion mechanisms may lead to more efficient oil recovery than either mechanism alone.

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Casteel J.F., and Djabbarah, N.F., "Sweep Improvement in CO2 Flooding by Use of Foaming Agents", SPE Res. Eng. November 1988

Tests results indicate that a WAG process implemented early will give better oil recovery than one implemented later in the flood. Two methods were used to inject foaming agents into cores. The first method involved injection of a foaming agent slug into two WATER-FLOODED Berea cores. The foaming agent was followed by a slug of CO2. In a few tests, this cycle was repeated. In the second method, CO2 was injected until no more oil was recovered from either core. An aqueous slug of foaming agent was then injected followed by CO2. This cycle was also repeated in some of the cores. A 154 md core and a 24 md core was used. The method that gave the highest oil recovery was when foaming agent was injected after CO2. The method involved injecting CO2 until no more oil was produced from either core. The CO2 was then followed by a small slug of 1.0% foaming agent. Another CO2 slug was injected and oil recovery determined. Results indicate that the CO2 slug preferentially flowed through the more permeable core, where it recovered most of the oil. The foaming agent also went preferentially into the more permeable core, where the CO2 had previously gone. This led to the generation of in-situ foam, which caused the following CO2 slug to divert into the less permeable core and recover most of the oil. This recovery is contrasted with the case where foaming agent was injected first. In such a case, an aqueous slug containing surfactant was simultaneously injected into two waterflooded cores and then followed by a CO2 slug. This resulted in a recovery of most of the oil from the less permeable core, but recovery from the more permeable core dropped subtantially. The explanation is that most of the foaming agent went into the most permeable core; likewise, most of the CO2 also entered into this core. The CO2 dispersed in the aqueous foaming agent slug, generated foam and increased the resistance to flow. The resistance to flow in the more permeable core increased to such a level that it caused the remaining CO2 to go into the less permeable core where it contacted and recovered most of the residual oil. One major result is that the sequence of injection affect the sweep efficiency of a CO2 flood. Also foaming agents can improve sweep efficiency of the CO2 flooding process.

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Castenier, L.M., "Steam With Additives: Field Projects of the Eighties", Journal of Petroleum Science and Engineering, 2 (1989) 193-206

The results have ranged from excellent to negative. Sixteen field tests of steam with additives have been studied. The results show that use of additives with steam can provide signifant benefits over the use of steam alone.

Introduction of air or oxidants can cause rapid degradation of the surfactant, addition of brine is positive with some surfactant systems (notable alpha olefin sulfonates) while it has a negative effect on some others. Two mechanisms can be identified for the effect of surfactants on steam injection: 1) a detergency effect, including dissolution of the asphaltenes and modification of the wetting characteristics of the rock and of the oil/water relative permeability curves. 2) diversion of the steam towards unswept areas of the reservoir through foam generation. This mechanism benefits from the presence of a noncondensible gas phase. Author determined that the economic use of additives with steam are favorable.

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Mohammadi, S. S. and McCollum, T.J., "Steam-Foam Pilot Project in Guadalupe Field, California", SPE Res. Eng. Feb 1989

Describes the use of a formulated alkyl toluene sulfonate (ATS) as a foaming agent for improving mobility control in a mature steam drive. The field results show production response to both the injectivity tests and the 9 months of continuous ATS injection. Overall, ATS was found to improve steam mobility and result in incremental oil production.

As a result of injection wellhead pressure data, which showed the rate of increase being a function of concentration, they suggested that in a continuous injection scheme, initial conc. should be high to reach a high pressure level quickly. The conc. may thereafter be reduced. They felt that this also proved that slug injection is detrimental.

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Mohammadi, S.S., Van Slyke D.C., and Ganong, B.L., "Steam-Foam Pilot Project in Dome-Tumbador, Midway-Sunset Field", SPE Res Eng, Feb 1989

Describes a steam-foam pilot project in the Potter sand, Midway-Sunset field. The pilot consists of four inverted five-spot patterns with a confined producer covering 5.2 acres. Steam foam was generated by continuous injection of steam with NaCl, alpha-olefin sodium sulfonate(Enordet AOS 1618), and nitrogen. Production and subsurface data, obtained from two observation well, were used as monitoring tools in the pilot. Overall, during the first 2 years of foam injection, 207,000 bbls of incremental oil was produced.

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Huh, D.G., and Handy, L.L., "Comparison of Steady- and Unsteady-State Flow of Gas and Foaming Solution in Porous Media", SPE Res Eng. Feb 1989

Brine or foaming solution was injected by a constant-rate pump and nitrogen gas was injected by a constant-pressure regulator. The surf. was Suntech IV, an alkyl toluene sulfonate with an averate of 16 carbon atoms. The critical micelle conc are 0.2% in distilled water, 0.02% in 0.5% NaCl solution and 0.04% in 1.0% NaCl. (This study used only 0.5% NaCl). All data were obtained from Berea sandstones 25cm long and 5cm in diameter. The measured permeabilities were from 400 to 600 md.The unsteady state experiments displaced a surfactant saturated core with nitrogen at CONSTANT PRESSURE DROP with no additional surfactant introduced. In the steady-state method, the core was also saturated with surfactant solution, but injection of nitrogen was simultaneous with injection of additional surfactant solution.(I don't see how they expect to compare these two very different conditions, but the comparisons within a given procedure should be useful).

Unsteady-state: the gas breakthrough time and gas saturation at breakthrough were considerable increased compared with the case of brine solution and nitrogen gas. The gas saturation at breakthrough between the concentrations of 0.2 and 1.0%, however, did not change much despite the large difference in breakthrough time. Results showed that foam decreases the mobility of gas by a factor of 20 even at surfactant conc. of 0.02%. Results show that the residual water saturation in the presence of foaming solution is about 10% lower than in the absence of foaming solution. However, it did not change with further increase in the range of 0.02 to 1.0%. Water relative permeabilities, while showing some very slight difference with and without surfactant, in general were not sensitive to the presence of surfactant.

Steady-state: As in the unsteady-state method, the relative permeabilities to water are close to each other and the relative permeabilities to gas int the presence of foaming solution are much lower than the reference rel perm. In all steady stae experiments, gas flow was completely blocked by foam lamellae generated by the simultaneous injection of foaming solution and nitrogen gas until the gas saturation reached 35 to 40%. After this critical saturation, the relative permeability to gas increased rapidly with a small increase of gas saturation (called a critical gas saturation). (note that this critical gas saturation was not the case for the unsteady-state runs, where there was still some low perm apparent even at gas saturations of below 5%).

Results show that relative permeabilities to gas increase with increasing pressure gradient. Because the expansion of the gas bubbles is an important factor in the rupture of foam lamellae, the mobility of the gas phase increases with increased gas expansion at higher pressure gradients.

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Persoff, P., Radke, C.J., Pruess, K., Benson, S.M., Witherspoon, P.A., "A Laboratory Investigation of Foam Flow in Sandstone at Elevated Pressure", SPE 18781 April 1989

In summary, foam flowing in porous media is a rheopectic fluid which at steady state is pseudoplastic with respect to gas fow and Newtonian with respect to liquid flow. Foam exhibits fascinating multiple personalities. Apparently, the foam texture adjusts to set a flow resistance that is compatible with a constant and low liquid saturation in the core. Because of the strong coupling between foam flow and foam texture, progress at quantifying the rheology of foam can only be made by directly measuring bubble-size distributions.

A 2 inch diameter and 24 inch long core of Bose sandstone was used. The core porosity was 0.25 and one pore volume was 300 cc. The foamer solution was a brine containing Na, Mg, and Ca, with 1% by weight surfactant. Two alkylethoxysulfates were used: Enordet AES 1215-9S or Steol 7N.

The typical experiment was a displacement by simultaneous injection of aqueous surfactant solution and nitrogen at a fractional gas flow or inlet foam quality from 70 to 96% into a core that had been initially saturated with the surfactant solution. CONCLUSIONS: The following conclusions are drawn for 1sq micrometer sandstone at about 700 psia back pressure and for total superficial gas velocities between 1 to 45 m/day and foam qualities between 70 and 99.5%. 1) During transient foam flooding of a surfactant-solution saturated core, the foam flow resistance builds in time and continuously varies from that chracteristic of free gas to that of a strong, fine-textured foam. 2) Steady foam flow resistance increases with increasing liquid velocity but decreases with increasing gas velocity. NO hysteresis observed. 3) Although foam flow resistance varies with flow rate, liquid saturations at steady state do not. They are constant at 0.3 to 0.35, independent of flow rates and foam quality. Therefore, foam flow resistance is not a unique function of liquid saturation. 4) Liquid flow resistance during foam flow obeys Darcy's law and exhibits the standard relative permeability pertinent to the core liquid saturation, independent of liquid and gas flow rates. 6) The most crucial parameter controlling foam flow resistance in porous media apparently is the bubble texture.

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Lau, H.C. and Borchardt, J.K., "Improved Steam Foam Formulations: Concepts and Laboratory Results", SPE 18783 April 1989

Conclusions: 1) Kern River pilot results indicate that a steam foam foam formulation based on AOS 1618 improves vertical sweep and, hence, oil recovery of a steam drive. However, the foam propagates relatively slowly and leaves the same ROS as to steam. 2) It follows that there are three distinct opportunities for improving the Kern River pilot formulation: a)faster surfactant propagation rate b) increased foam strength and c) ROS reduction (residual oil saturation) 3) Formulations developed to exploit these opportunites have included: a) variation of NaCl and surfactant conc. b) addition of a cosurfactant c) used of alternative field-tested steam foam surfactants Suntech IV and Chevron Chaser SD1000, d) addition of alkali e) use of disulfonate-enriched AOS 2024 (checked by Farid as AOS2024DE) f)use of AOS 2024 monosulfonate with Na2SO4 as the injected electrolyte. 4) Only the alkaline, AOS 2024 disulfonate, and AOS 2024 monosulfonate formulations were found to achieve all three desired improvements. 5) In the alkaline design, addition of Na2CO3 or trona ore improves surfactant propagation by precipitating divalent ions. ... 6) Use of higher molecular weight AOS (2024) incrases foam strength and reduces ROS. However, surfactant propagation suffers if something else is not done. There are at least two ways to improve surfactant propagation. One is to increase the disulfonate content in the surfactant. The other is to use sodium sulfate as the injected electrolyte to precipitate the calcium. 7) Site-specific studies have to be conducted with reservoir sands, oil, and synthetic field water to determine the suitability of each design for the target reservoir.

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Di Jullo, S.S., and Emanuel, A.S., "Laboratory Study of Foaming Surfactant for CO2 Mobility Control", SPE Res. Eng. May 1989

The effectiveness of foam as a mobility-control agent has been tested by an immiscible CO2 coreflood displacement of a California heavy oil (14 API). Foam was produced by simultaneous injection of 0.5 wt% surfactant solution and CO2. Foam injection recovered an incremental 33.6% of oringinal oil in place by reducing CO2 mobility and diverting CO2.

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Falls, A.H., Musters, J.J., and Ratulowski, J., "The Apparent Viscosity of Foams in Homogeneous Bead Packs", SPE Res. Eng. May 1989

The mobilities of aqueous foams of known texture have been measured in homogeneous bead packs. To correlate the data, a theory developed recently to describe the apparent viscosity of foams in smooth capillaries is extended to account for 1) capillary pressure imposed by the porous medium, and 2) constricted flow paths. In porous media, apparent gas viscosity depends strongly on foam-bubble size; for large bubble sizes, it is proportional to the third power of the ratio of the hydraulic radius of the pack to the bubble radius. Foams of uniform texture are pseudoplastic. At low shear rates, the viscosity varies inversely with capillary number(note that at low rates the results are independent of bubble size) ; at higher rates, it depends on the capillary number to the -1/3 power when the bubble size is large compared with the pore size and on the -2/3 power of capillary number when the bubble size is smaller (ie on the order of the pore size –my note).

Foam generators were used.

When the injected gas fractional flow was within certain limits (and only these limits) and the gas flow rate was sufficiently low, the foam texture did not change in situ. and almost all liquid was transported within lamellae. For this case the bubble sizes were much greater than the equivalent capillary radius of the porous media. In this mode, much of the cross-sectional area was blocked by stationary lamella, and moving lamella used a single flow path to traverse the pack. When a bubble size was injected that was on the order of the equivalent capillary radius, the pressure gradient was high and there were few stationary lamellae; i.e most of the gas in the pack was flowing.

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Hirasaki, G.J., "The Steam-Foam Process", JPT May 1989

The steam foam process was developed to improve the sweep efficiency of the steamdrive and steam-soak processes. Steamdrives that are not stabilized by gravity can have poor vertical sweep efficiency as a result of 1) gravity overlay in a thick sand with vertical communication and/or 2) channelling in a layered formation with poor vertical communication between sand member. The reduced mobility of steam foam increases the pressure gradient in the steam-swept region to displace the heated oil better and to divert steam to the unheated interval.

Surfactants reduce the steam mobility by stabilizing the liquid lamellae that cause some or all of the steam to exist as a discontinuous phase. The propagation of surfactant is retarded by adsorption. In the case of ion exchange of divalent ions from the clays, the surfactant is also retarded by precipitation and/or partitioning into the oil. The rate of propagtion of foam is also determined by the mechanisms that generate and destroy foam. The generation mechanisms include leave-behind, snap-off, and division. The destruction mechanisms include condensation and evaporation, coalescence by a limiting capillary pressure, and coalescence resulting from the presence of oil. The foam texture can be predicted from a population balance that includes these mechanism.

GRAVITY OVERRIDE: The steam drive process is very efficient and there is little potential for foam when the effect of gravity makes a large contribution to the flux of the heated oil from the injector to the producer (downdip) and/or from the gas/oil contact (GOC) to the perforated interval or pump off-take level. On the other hand, steam will override the reservoir, and poor vetical sweep will result, if a reservoir (or a sand unit of a multizone reservoir) has nonzero vertical permeability and does not have high enough dip and/or horizontal permeability. Such a reservoir has a good potential for the application of foam.

CHANNELING: Chanelling is defined as the loss of steam to isolated "thief zones" that take a disproportionate amount of the injected steam. The thief zone could be either a zone of high-permeability sand or a gas-filled, desaturated zone that is isolated from the other zones except at the wellbore. A thief zone in a steamdrive or steam soak is much more severe than in a waterflood because once the zone is desaturated, the high mobiilty of steam compared with the viscous oil and water causes the thief zone to be a "short circuit" for the subsequently injected steam.

Correction of the injection profile will correct the vertical sweep in the reservoir if there is indeed no cross flow in the reservoir. Foam will improve the injection profile by reducing the contrast between the resistance in the desaturated thief zone and that in the oil-saturated zones. Because the resistance of the radial flow from an injection well is concentrated in the vicinity of the well, the foam mobility in the vicinity of the well is much more important than that farther into the reservoir. Thus, it is not necessary to propagate foam across the entire reservoir to achieve an improvement in the injection profile in a reservoir with no crossflow.

Even if there were no incremental ultimate oil recovery with steam foam, acceleration of production from improvement of the cumulative oil/steam ratio is equivalent to an increase in net oil recovery because of savings in the crude oil burned for fuel to generate steam. This conservation of steam suggests that the steam-foam process should be started soon after steam breakthrough rather than after the economic limit of conventional steamdrive.

Modes of Application: Continuous or Slug Injection: The steam-foam additves have been added to the injected steam either as 1) a continous process at some specified concentration, 2) slugs at some specified concentration added to steam (at a quality of about 60%) alternated with conventional steam injection 3)slugs at some rate (eg gallons per minute) added to the steam alternated with conventional steam injection or 4) slugs of concentrate added to the steam injection stream. (note that none of the ones mentioned are a situation where the steam injection is stopped)

The role of noncondensible gas is to stabilize the collapse of bubbles of steam by condensation. The greatest effect of the NC gas is deep in the reservoir where a significant component of the mobility reduction is caused by the presence of trapped bubbles. A small amount on NC gas will greatly extend the life of a trapped bubble compared with a bubble of pure steam.

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Huh, D.G., Cochrane, T.D., and Kovarik, F.S., "The Effect of Microscopic Heterogeneity on CO2-Foam Mobility: Part 1- Mechanistic Study JPT Aug 1989

Results show that foam can be generated by upstream and downstream snap-off. Fluid diversion was obtained not only by lamellae and foam, but also by multiple interfaces of CO2, surfactant solution, and oil, depending on the pore structure of the micromodel. The most important factors in the in-situ generation of foam, however, were the mixing of fluids and the aspect ratio of the pore structure. The surfactant cas Alipal CD-128, with NaCl concentrations varying from 0.0 to 5.0%. CMC was found to be 0.2%. Four micromodels were used, with varying degrees of heterogeneities. In the displacement experiments, pure CO2 was injected into 100% saturations of brine or surfactant solution. In other runs, CO2 and surfactant solution at 4:1 volumetric ratio were simultaneouly injected into either 100% surfactant solution, oil at interstitial water saturation, or waterflood residual oil saturation.

In addition to traditional snap off , a different type was observed, ie. upstream snap off, which occured in the heterogeneous models. When a slug of surfactant solution is injected into a CO2 swept zone, the surfactant solution flows along the wall of the pore body. Then this wetting phase pinches off the nonwetting phase at the leading edge of the surfactant solution. The size of the bubbles generated by upstream snap-off is usually larger than the bubbles generatiee by downstream snap-off. A highj aspect ratio is not necessary either. One important point to remember is that downstream snap off usually occurs when the nonwetting phase is injected into the wetting phase saturated porous medium, while the simultaneous injection of CO2 and surfactant, or the injection of a surfactant slug into a CO2 saturated zone usually results in upstream snap-off.

Foam generation increases compared with single phase pure CO2 injection when CO2 and surfactant solution are injected simultaneoulsy. The mixture of pore-space fluids and the pore-body/pore throat aspect ratio are the most important factors in foam generation.

Lamellae in a less heterogeneous model appeared to more stable, possibly because in the heterogeneous model, the constantly changing pore sizes stretch the lamellae, while in the unifor model the pore radius is more uniform and the lamellae can travel longer distances without ruptureing.

Bubble generation at the inlet portion of the model promotes the mixing of CO2 and surfactant, csusing additional foam generation downstream.

Foam generation and stability were adversely affected by an oil phase. Foam bubbles coalesced or ruptured and foam generation was inhibited when foaming agents flowed into an oil zone.

The change in the micromodel wettability caused by contact with oil phase was another important factor in the displacement experiments. Saturating the models with crude oil changes the wettability to intermediate or oil-wet, greatly reducing foam generation due to lack of surfactant at foam generation sites.

Higher surfactant conc. promoted more foam generation and improved sweep efficiency, however no significant differences in bubble size were observed with increasing surf. concentrations. Foam bubbles at higher surf. conc. exhibited greater stability and were displaced over long distances through the micromodel without rupturing and coalsescing.

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Buckley, J.S., Takamura, K., and Morrow, N.R., "Influence of Electrical Surface Charges on the Wetting Properties of Crude Oils", SPE Res. Eng. August 1989

Reservoir wettability is important to oil recovery by waterflooding and many other oil recovery processes. The difficulties associated with determination of in-situ wettability, together with uncertainties about application of laboratory observations to field conditions, necessitate a more basic understanding of factors that control wettability. In previous work, we reported that adhesion of crude oil to a solid surface could be related to wettability changes. In this work, conditions under which oil adheres to a particular solid surface are demonstrated for several crude oils. For a given oil, pH and ionic strength were varied to obtain a mapping of conditions under which adhesion occurs. Lack of adhesion signifies the presence of a stable water film that results from double-layer repulsion between the crude oil and the solid surface.

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Sanchez, J.M. and Hazlett, R.D., "Foam Flow Through an Oil-Wet Porous Medium: A Laboratory Study", SPE 19687 October 1989

Conclusions: 1) Gas permeability is significantly reduced under conditons of steady, two phase flow of gas and surfactant solution through a silanated beadpack, compared to that in the absence of surfactant. This indicates that foam forms in-situ, in an initially oil-wet porous medium, in the presence of surfactant. 2) Foam formation, in the initially oil-wet porous medium, is a result of wettability alteration of the hydrophobic solid to hydrophilic. This reconciles the data with foam generation theory–all of which rests upon the assumption of a water-wet network. 3) Wettability alteration is evidenced by a substantial shift in the liquid phase relative permeability of the initially oil-wet media when surfactant is present. 4) Liquid relative permeability curves, in the presence of surfactant, for the initially oil-wet porous medium essentially match those for water-wet media, both in the absence and presence of surfactant. 5) The observed wettability change is due to surface tension lowering and surfactant adsorption and is a general phenomenon associated with the gas-brine-hydrophobic soid system. 6) Gas permeability reduction for the same surfactant concentration is essentially identical for both water-wet and initially oil-wet media. This further supports the assertion that the initially hydrophobic surface has been altered to hydrophilic.

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Ettinger, R.A. and Radke, C.J., "The Influence of Texture on Steady Foam Flow in Berea Sandstone", SPE 19688 October 1989

The porous medium is a fired Berea sandstone 8inches long, 4 inches wide, and 0.4 inches deep. The absolute permeabilty is 0.8 sq. micrometers and a porosity of 24 percent. The surfactnat solution is a degassed, saline solution containing 0.83 wt% NaCl with 0.83 wt% active C14-16 alpha olefin sulfonate (Bioterg AS-40). The core is vacuum saturated and replentished with approximately 5 PV of surfactant solution. Nitrogen and foamer solution are injected either directly into the core or first into the pregenerating core until steady state is achieved. If the pregenerating core is on-line, a steady-state foam texture is first produced with flow directed into the surfactant filled downstream core. Steady state in the working core is typically established after about 10 pv and is assessed both by unchanging pressure and liquid saturation profiles and by observing constant inlet and effluent foam textures. The average gradient for a typical run was 74 psi/ft. With such large pressure gradients and an atmospheric exit pressure, gas compressibility cannot be ignored. For example in a typical run the gas velocity increases down the core by a factor of 3 and the foam quality increases by 40%. Inlet bubble sizes for the strong foam are typically near 80 micrometers while those exiting were typically near 300 micrometers. The pressure profiles indicated that generation and coalescence mechanisms shape the foam over very short distances near the core inlet. Liquid saturations are constant at several units above connate saturation and are independent of gas flow rate. Likewise, foam pressure gradients are also sensibly independent of gas flow rate when the liquid velocity is fixed. Either injection of a fine texture foam, whith bubble sizes near 80 micrometers or injection of unfoamed gas and surfactant solution yields effluent bubble sizes near 300 micormeters. The porous medium shapes the foam to its own liking through strong making and breaking processes.

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Yang, S.H. and Reed, R.L., "Mobility Control Using CO2 Foams", SPE 19689 October 1989

Mobility reduction caused by CO2 foams that are "stable" or "unstable" in the bulk phase was studied in Berea sandstone and San Andreas carbonate outcrop cores at 100 F and 2000 psi. Depending on hydrophilicity, some surfactants led to foams having a favorable dependence on permeability and oil saturation whereas another did not. Foam mobility was found "shear thinning" at high flow rates and "shear thickening" at low rates. Bubble coalescence was investigated in relation to snap-off, transport, and trapping. Unless otherwise specified, all cores had dimensions of 1"x1"x12". Most in-situ foam generation experiments were carried out in water-flooded cores using dual -bank injection: ie. 3 to 5 PV of surfactnat followed by 2 PV of CO2. Decane was the oil phase. The standard brine contained 5.6 wt% NaCl and 1.4 wt% CaCl2. Waterflooding and surfactnat preinjected were carried out at 3 ft/day. No oil was produced during surfactnat injection. CO2 injection was carried out at 1 ft/day with exceptions occuring, as noted, when studying effects of flow rate and permeability. The surfactant conc. was 0.1 wt% in all test(many types used).

The foam was almost non-existent at oil saturations larger than 20%, but effective at oil saturations less than 5%. In this study, the presence of decane in the CO2 phase (it was injected in the gas phase) destabilized DPEDS foam.

RThe effect of permeability on DPEDS foam was studied in both sandstone and carbonate cores. Comparative foam mobility decreased from 2 to 0.15 as the permeability of sandstone increased from 150 to 400 md. Comparative foam mobility decreased from 3 to 0.8 as the permeability of carboneat increased from 40 to 140 md. These trends are similar., hence the results show that foam mobility decreases as the pore size increases in both sandstone or carbonate rock.

The effect of permeability was also studied for NES-25 foam. Comparative mobilities were 0.15 and 0.3 in 450 md and 120 md Berea cores. Both DPEDS and NES foams followed the decreasing trend, but the former was more effective in reducing CO2 mobility in high permeability cores. Oil recovery using NES foam was substantially less than that obtained using DPEDS foam. Since NES forms oil-water emulsions in bulk phase tests and DPEDS does not, these results suggest that the difference in permeability dependence is partilally a consequence of emulsions generated in situ by NES.

We considier two cases to diagnose mechanisms of foam flow using either DPEDS or NES surfactant. On the one had, suppose bubbles coalescence time is relatively short so thin films cannot travel through pore thoats without rupture. The foam propagation is mainly by breaking and reforming of thin films. Thin films can be thought of as "gates" to CO2 flow. The longer they live, the more resistance to flow. Sonce coalescence time decreases as pore size decreases(fig 5 - their model) it is expected that foam mobility is higher in less permeable zones. On the other hand, suppose bubble coalescence time is extremely long. In this event, bubbles will tend to flow without rupture in "trains" causing extremely high pressure gradients; or ceasing to flow altogether if there is a pressure gradient limitation, as there is in reservoirs. In this event, based on previous discussion on bubble train movement, foam mobility increases with permeabiliuty.

The permeability dependence of DPEDS foam suggest that its propagation is mainly due to breaking and reforming. The permeability dependence of NES foam suggests that its propagation is likely to involve not only breaking and reforming of films but also some movement of bubble trains.

Discussing previous researchers, he shows Galls work where Gall found almost no dependence of mobility on permeability, although mobility decreased slightly for increasing permeabilty (the range of about 2 to 80 darcies was checked). He also discusses Khatibs work with alpha olefin sulfonate foams in sandpacks where the found the foam mobility increased signifcantly as the permeability increased from 70 to 10000 darcy. Yang gives the explanation that in Khatibs case, the foams were extreemely stable and bubbles and thin films probably flowed together in the "bubble train" mode.

Also states that most studies are in systems with permeabilities that are unrealistically high for most reservoirs.

EFFECTS OF FLOW RATES: In our experiments, the comparative mobility of SPEDS foam in 400 md Berea cores increase from 0.15 to 1.0 as the flow velocity increased from 1 ft/day to 9 ft/day, following a "shear thinning" trend. The foam mobility did not change much as the flow velocity decreased from 1 ft/day to 0.5 ft/day. However, the comparative foam mobility increased from 0.15 to 0.5 as the rate further decreased from 0.5 ft/day to 0.1 ft/day, following a "shear thickening" trend. Both "shear thinning" and "shear thickening" trends can be interpreted in terms of the relative effects of flow rate on bubble snap-off and coalescence. The driving pressure for bubble coalescence increases as the flow rate increases. Figure 3 (their model) shows that bubble coalescence time decreases with increasing driving force. Therefore, thin films live shorter resulting in less resistance to CO2 flow. The fact that at high rates snap off is more efficient cannot counteract the detrimental effect of high rates on coalescence, hence at high rates, a shear thinning trend is observed where increaseing rate gives increasing mobility. In the transition zone, the rate is less, so coalescence occurs slower, however, snap off is also less efficient. The two balance each other and foam mobility is constant over a short range of gas flow velocities. At even lower rates, the effect of the low rate has a more detrimental effect of snap off, and coalescence is even slower (which is better). In this region, increasing velocity has a large effect of snap-off, making it more efficient, and coalescence is not detrimentally effected by increasing velocity in this region, so increasing velocity causes decreasing mobility, in a "shear thickening" trend.

SURFACTANT HYDROPHILICITY AND FOAM STABILITY: Surfactant retention increased as surfactant hydrophilicity decreased. In general, foam lifetime increased as surfactant hydrophilicity decreased. For a homologous series of surfactants, the relation between hydrophilicity and coalescence time may originate from lower surface concentrations for the more hydrophilic species; possibly implying lower surface viscosities and surface tension gradients, leading to unstable foams.

CONCLUSIONS: 1) The effect of permeability of foam mobility depends on surfactant hydrophilicity and foam stability. The trend is that more stable foams give less favorable or even unfavorable permeability effects (bubble train mode). 2) A film drainage model was developed. 3) Two foams exhibiting different stabilities in the bulk phase may result in the same mobiity reduction to CO2 flow in rock inder certain conditions. Fast film breaking and reforming may be as effective as slow film breaking and reforming.

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Kular, G.S., Lowe, K., and Coombe, D., "Foam Application in an Oil Sands Steamflood Process", SPE 19690 October, 1989

This paper outlines a foam field test presently being conducted in the McMurrary formatin of the Athabasca Oil Sands in Alberta. Prior to initiating the test various surfactant were tested in the laboratiory by injecting with steam into a sandpack. Lab results also indicated that the simultaneous injection of surfactant, steam and a non-condensable gas provided a higher pressure increase compared to batching the surfactant ahead of the steam and gas.

Lab testing: the flow of the brine was maintained to keep steam quality of 80%, corresponding to the average field quality. The pressure gradient increased sharply when the surfactant conc. was two grams per liter and dropped rapidly when the conc. was decreased to one gram per liter. There was no further increase when the conce. was increased to three grams per liter. Concerning NC gas, the foam was stable at injection rate varying from 0.5 to 3.0 mole % of the qualitative understanding of fluid flow. Since the film thickness is proportional to gas velocity cubed, then in the constriction the film thickness should be greates since the velocity will have to increase though the constriction. Not all constricted, cornered pores admit snap-off. Wetting liquid always flows into the constriction, but, depending on the value of throat to capillary radius, not enough liquid may accumulate at the neck to acheive the critical unstable configuration. Only pore body to pore throat aspect ratios of approximately 2 or more admit constriction neck snap-off. This purely static criterion was first put forward by Roof and now bears his name.

It can be reasoned(and checked experimentally) that for snap-off in constricted cornered pores when the tube capillary number is so low that thin films are negligible and the deposited pendular liquid saturation is that extablished at the equilbrium entry capillary pressure, that the deposited corner liquid saturation profile is independent of the gas velocity. It has indeed been shown experimentally that for capillary numbers less than about 5(10-4) that the dimensionless snap-off time is independent of gas velocity, which is not the case for constricted circular capillaries. Another difference between constriced cornered capillaries and constricted circular capillaries is that surfactants do have a minor affect on the snap-off time in the former but not in the later. The independence (at low velocities) of snap-off time with gas velocity requires that the bubble size produced in a single constricted and grooved pore should increase linearly with gas velocity, since the bubble travels a distance proportional to the product of its velocity and the snap-off time. This has been experimentally confirmed

(note: in very sharply constricted geometries, snap-off is actually inhibited since the large transverse curvature prevents inflow into the neck.

Preneck constriction snap-off: Preneck constriction snap-off in a cornered constriction is distinguished from neck constriction snap-off in that the advancing gas finger actually stops as opposed to traversing across the entire constriction. It results in bubble sizes that are about the size of the pore-throat, subtantially smaller that neck-contriction snap-off which is on the order of one to several pore bodies. If the velocity of the bubble approaching the constriction is not sufficiently large, the bubble is trapped and held somewhat upstream of the neck by the balsnce of surface tension forces preventing entry and the applied liquid pressure gradient forcing weeping flow along the corners of the pore. For a given size bubble and constriction geometry, there is a critical value for the weeping flow rate, reflected quantitatively by a dimensionless mobilization capillary or weeping number for corner flow, at which the bubble front curvature just matches the equilibrium entry curvature of the pore throat. When this happens, the trapped bubble squeezes through the constriction.

We anticipate bubble sizes near that of several pore bodies. Provided that reentry times of the advancing finger through the constriction are smaller than snap-off times,(ie the gas is beyond the Roof criteria), then the frequency of bubble genration should be independent of gas flow. Conversely, if the emerging bubble nose travels very slowly, then once it reaches that point in the pore body where the Roof criteria is met, the corner fluid has already reararanged into the unstable collar configuration and snap-off is instantaneous. In this case, the bubble size is close to, but somewhat smaller than the pore body. In this case the bubble generation frequency should increase with gas velocity.

Thus a porous medium displays specific locations, called germination sites, where snap-off occurs. Surfactant plays a secondary role. Snap-off is rampant in porous media during multiphase flow irrespective of the presence of surfactants.

COALESCENCE

As opposed to snap-off, surfactants and thin film forces constitute the decisive factors in foam coalescence. With no surfactants the lenses that are generated by snap-off drain and break whenever the two newly created interfaces are forced into contact during flow. Lamellae are sustained only when surfactants are present.

To understand the need for surfactants, consider a static lamela with anionic surfactant at the gas/liquid interface. In porous medai, lamellae span the pores and are bowed at 90 degree angles to the pore walls, however, because lamellae are so thin (100 nm) they may be considered flat in a discusiion of their intrinsic stability. Also, the lamella terminate in thick fluid regions known as Plateau borders. The liquid pressure in the Plateau border is lower than that of the gas according to the Young-Laplace equation. Inside the lamela, the total liquid pressure (normal stress) must equal the gas pressure since the curvature is zero. Hence the Plateau border exerts a suction on the lamella and attempts to drain all the liquid out. A way for foam lamellae to overcome the Plateau-border suction is if additional normal stress, over and above the buld liquid pressure, exists due to the extreme thinness of the liquid film. This additonal normal stress is defined as PI, which is the conjoining/disjoining pressure. This PI is positive for repulsion (disjoining) and negative for attraction (conjoining). Lamellae in porous media can balance the capillary-suction only if PI is positive. The recognition of thin-film forces demand a correction to the basic Young-Laplace eqn, with the additon of PI making the equn. more general. This is known as the augmented Young-Laplace relation. In strongly wetting porous media, it is expected that the capillary suction pressure exerted in the Plateau borders is very close to the mean capillary pressure of the medium, because the pore grooves and channels permit liquid transport to equalize any local gradients in the capillary pressure. To a first approximation, PI depends only on the lamella thickness h. The combined value of PI can be considered to be comprised of three separate components. The first is an attractive force and leads to coalescence. This attractive force is the result of Van der Waals dispersion forces between gas molecules across a given lamella. A second contribution to PI is repulsive. Adsorbed anionic surfactants impart a net charge to each of the two gas/liquid interfaces of the lamella. An ionic cloud in the adjacent solution, called generically the electrical double layer, neutralizes this adsorbed charge. Upon close approach of the two interfaces as h diminishes, the two ionic clouds overlap and least to a positive or repulsive disjoining pressure. The third component to PI (also repulsive) arises when there are very close separtations (on the order of molecular scales) between the bubbles, it is thought to originate from solvation forces and/or molecular crowding. Note that both repulsive portions of PI originate from the presence of surfactants. At equilibrium, the capillary suction pressure just balances the conjoining/disjoining pressure. Also, the authors conclude that lamella are state when the initial thickness h is in a region where the derivative of PI with respect to h is negative, and unstable when the derivative is positive. (The authors point out that this conclusion was first reached by Vrij(196) using s thermodynamic approach. So, there does exist a stable thickness, although stability strictly refers to metability since breakage of the film lowers the overall system free energy by destroying surface area (my note: also by destroying surface area, it enables the concentration on the remaining surface to increse, hence lowering surface tension further.).

Experimental conj/disj pressure isotherms for the anionic surfactant sodium dodecyl sulfate at 0.03 wt% in two NaCl brine were reported. The values of PI are surprising large(up to 15 psi) even for the dilute conc. used below the cmc. Only the negative sloped section of the isotherm is attainable experimentally. Also experimentally, there is a hysteresis observed during the imbibition vs drainage procedure, with the jump from one negative slope to the other negative slope being different.

The authors speculate that the extremely thin, Newton black films are not robust enough to survive application in porous media, and that only lamellae thicker than hc can exist in porous media. Once the mean capillary pressure of the porous media rises to PImax then all lamellae in the medium must collapese. Thus in a given medium, there is a particular low wetting liquid saturation, or equivalently, a specific high capillary pressure (PImax) at which foam cannot exist. In dry porous media with low wetting liquid saturations, foam will be difficult to stabilize. Likewise, at a given wetting liquid saturation, porous media with low absolute permeabilities tend to destabilize foam because they exert large capillary pressures. Surfactant formulatin for foam stability has its origin in increasing Pimax.

DYNAMIC LAMELLEA:

An additional ingredient of foam stability arises for lamellae that transport in porous media. Near a pore throat the lamella is thick, whereas near the pore body the lamella is thin as it conforms the wall shape. During this stretching and squeezing, if the lamella emerges from a pore throat to a pore body with a large aspect ratio, Rb/Rc, its thickness will fall below hc, and the result is coalescnece. So, as in snap-off, constriction geometry is important. This scenario requires that foam lamellae fill or empty to alter their thickness in reponse to the capillary pressure applied in the Plateau border. When Pc is raised the film thins to a new equilibrium state and vice versa. Thus during transport through pore throats and bodies, the lamella fills whenever the value of PI corresponding to the instantaneous, local film thickness rises aboe Pc. Conversely, whenever PI falls below Pc, liquid drains from the film.

Interaction of the processes of strecthing/squeezing due to volume rearrangement and filling/draining die to capillary pumping causes the translating film to oscillate in thickneww about the equilibrium value, where Pc = PI. If the oscillations are wide enough, then h will fall below hc, and coalescence will occur. These larger oscillations would be expected to occur for higher gas velocities (since pumping in or out would have trouble 'keeping up'), and for higher aspect ratios Rb/Rc. So, for a given gas flow rate and pore geometry there exists a limiting or critical capillary pressure, below the static limit PImax, at which the lamella ruptures essentially instantaneously when compared to lamella pore transport and draining/filling times. We find that for strongly stabilizing surfactants limiting capillary pressures can be quite high, almost corresponding to connate water saturations. Dilute or ineffective surfactants may invoke rapid coalescence even at relatively high wetting liquid saturations. Authors state that little is known about the magnigude and shapes of the conj/disj pressure isotherms at the higher surfactatn conc. (well above cmc) typically used in foam flooding application.

FOAM GENERATION MECHANISMS

In the micromodel photographs, the foam bubbles are separted from the pore wall by thick aqueous cushions. Also, the dispersion microstructure is not that of bulk foams where the average bubble diameter is much smaller that the pore diameter, rather pictures showed that the discontinuous bubbles essentiallyfilled the pore channels as trains of bubbles coupled together by the intervening lamellae. The pictures also indicated that foam was the nonwetting phase.

Neck Constriction Snap-off: Two controlling time scales apply to the snap-off process: a convection time for the bubble front to emerge far enough into the pore body where the Roof geometric constraint is obeyed, and a drainback time for the liquid to flow into the throat. Also observed in the pictures was that as long as a downstream pore body remained relatively free of gas bubbles, the snap-off process repeated itself at a given germination site. Later, when the amount of gas in the pore body accumulated, snap-off quit at the given location.

This is the result of the increased local capillary pressure associated with the increased gas saturation, resulting in higher curvature of the bubble front, and too high a cap pressure. From this snap-off termination associated with a given site, the authors contend that snap-off is primarily important during transient drainage displacement, as gas enters Roof germination sites that are almost completely liquid filled. During steady state foam flow, neck constriction sanp-off will require repeated massive, intermittent invasion of wetting liquid into the Roof-site pore bodies. Thus, at steady state and especially at low liquid saturations, neck constriction breakup is NOT expected to be the dominant category of snap-off.

Preneck Constriction Snap-off: This type of snap-off occurs as wetting liquid, weeping around the bubble trapped against the constriction, induces a high liquid pressure gradient near the front of the bubble. The size of the foam bubbles created by preneck constriction sanp-off is of the order of the pore-throat diameter, not the pore body diameter. During liquid imbibition, preneck snap-off continues at a given germination site, resulting in the formation of many small gas bubbles from an original larger bubble. Generation frequency increases with the rate of weeping flow along the corners adjacent to the trapped bubble and hence with liquid flow rate.

Rectilinear Snap-off (termed upstream snap-off by Huh): This occurs in relatively straight pores that are longer than 2*pi*R, when the local capillary pressure falls and liquid invades to establish the critical corner saturation needed. Flow conditions, as in preneck constriction snap-off are again in the imbibition mode. Breakup occurs in the tightest part of the constriction, and the bubbles produced are considerably larger than those generated by preneck snap-off. Note that this type of snap off would not be expected to occur during a drainage displacement, and it is apparently the weeping flow during imbibition displacement that initiates breakup. In steady foam flow, rectilinear sanp-off appears to (the authors) to be a dominant bubble generation mechanism. We find that snap-off in this situation occurs mainly at pore throats (with lengths longer than 2*pi*Rt) along the backbone fraction of the gas flow network and at pore throats within short clusters of pores leading off the backbone which support alternating trapped and flowing bubble trains. Relatively smaller, but gas occupied, pore throats are more likely rectilinear snap-off sites than are larger throats, because they have higher critical breakup curvatures and because they become unstable for smaller capillary pressure fluctuations. Both gas and liquid flow rates are involved, with larger values of each generating bubbles more quickly.

Lamellae Leave-Behind: This can occur when two separate gas fronts converge on the same liquid-filled pore space from different directions. As long as surfactant is present to stabilize the interface and the capillary pressure in the medium is not too high, then a stable, stationary lamella results. The two gas fingers do not need to converge simultaneously on the same liquid filled region, rather a gas finger arriving at a later time can converge on an existing gas-filled channel and squeeze down the lamella as the capillary pressure increases. Generally, unless ruptured by a further increase in capillary pressure, or mobilized by an increase in the pressure gradient, the leave behind lamellae remain at their point of generation in the medium. If a leave-behind lamella does not vacate a generation site, substantial liquid must reinvade this region before a new leave behind lamella can be generated. Hence leave-behind is expected to be more prolific at high wetting-liquid saturations. Since some flow channels are blocked, some reduction in mobility is seen. The surrounding gas phase remains continuous.

Lamella Division: Lamella division demands the preexistence of flowing lamellae. However, once formed by snap-off or leave-behind, the number of flowing lamella can increase by the mechanism of lamella division. An observation about lamella division is that larger gas bubbles have a greater tendency to divide than smaller ones. When bubbles are smaller that the pore body, they flow through branches unaltered. However, larger bubbles, whose lamellae essentially span the pore body, do undergo division (micromodel observation). Two minimum requirements for lamella division are mobile lamellae and branching in the flow paths (ie germination sites). Bubble generation frequently varies directly with the gas velocity, while bubble size depends directly on the parent size.

FOAM TERMINATION MECHANISMS:

In the absence of oil, foam lamellae in porous media break by two mechanisms. Moving lamellae, coalesce when they are rapidly stretched across large pore bodies.. For a given gas flow rate and capillary suction pressure in the porous medium, pore-throat/pre-body combinations with large aspect ratios,(Rb/Rc), serve as termination sites. As the gas velocity and/or porous medium capillary pressure increases, more and more throat/body configurations become termination sites. Trapped or static lamelae break by a second mechanism. Whenever two bubbles with different curvaturee are in contact, gas diffuses from the more highly curved bubble to the less curved bubble through the intervening lamella. Eventually, the smaller bubble disappears along with the common lamella.

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Liu, D., Castenier, L.M., and Brigham, W.E., "Analysis of Transient Foam Flow in 1-D Porous Media With CT", SPE 20071 April 1990

Foam is injected at a constant volume rate into a one-dimensional sandpack of 1-inch diameter and 24 inch length, initially saturated with distilled water. Gas channeling appears near the front and eventually the foam blocks all these channels. The foam flows through the sandpack, continuously breaking and reforming. It takes two or more pore volumes of foam injection to reach residual liquid saturation. The surfactant used were AOS 1618 and SuntechIV. It was found for the range of surfactant conc. studied (0.1 to 1.0 wt%) that the higher conc. the better and faster the displacement. conclusions: 1) the higher the surfactant conc., the greater the pressure gradient, 2) gas channeling ocurs in the foam front of the displacement. It is not valid to assume a piston-like behavior. 3) the mechanism of foam propagation seems to be initial gas channeling, progressively becoming more uniform as foam blocks the channels.

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Kuhlman, M.I., Falls, A.H., Hara, S.K., Monger, T.G., Borchardt, J.K., "Carbon Dioxide Foam With Surfactants Used Below Their Critical Micelle Concentrations", SPE/DOE 20192 April 1990

It is advantageous t use surfactants below their critical micelle concentrations to reduce gas mobility throughout a reservoir. When used in reservoir brines below their CMCs, inexpensive anionic surfactants propagate through rock with little delay due to adsorption. Yet, gas mobility is reduced below that of a waterflood in either Surfactant-Water-Alternating Gas (SWAG) or coinjection experiments. Moreover, oil recovery is higher than in porcesses without surfactatn. In contrast, at concentrations above the CMC, surfactant adsoription is much higher and the injected surfactant concentration can be greatly delayed.

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Hanssen, J.E. and Dalland, M., "Foams for Effective Gas Blockage in the Presence of Crude Oil", SPE/DOE 20193 April 1990

A total of 48 foaming agents for aqueous and non-aqueous systems have been evaluated using a gas blockage test, as well as bulk foam stability tests and measurements of relevant surfactant properties. All experiments were performed in contact with sea water and crude oil at elevated temperature. A number of foams known to be efficient gas-blocking agents in oil-free media were non-blocking in the presence of residual oil. Bulk stability could not predict the gas-blocking ability for the foams studied. Further, no correlation was found between foam gas-blocking ability and the interfacial tensions, spreading conditions, oil saturation, foam quality, surfactant oil solubilization, or relative wetting abilities of surfactants measured. The four succesful products found are flourinated surfactants, and were effective at 0.5 to 1 wt%.

Spreading Coefficients: These have been thought important since spreading of oil on many foam films can be seen to cause their breakdown. A spreading oil gave a lower constant-rate pressure drop across a foam-filled core than did a non-spreading oil of otherwise same properties (ref Wasan). In the present study, all gas-blocking foams showed nonspreading oil, but so did several non-blocking ones. For spreading of the aqueous phase on oil, both positive and negative coefficients were found, indicating this property to be non-critical to gas-blockage. Nonspreading oil, from these data, may be said to be necessary, but not sufficient, to obtain a gas-blocking foam. It should be noted that spreading coefficients derived from bulk IFT may not always be applicable on a microscopic scale(Ref).

Foam Quality: is calculated as 0.92 for the blocking foams and 0.87 for non-blocking foams. (must be at exit)

Pseudoemulsion films differ from foam films by having oil on one side and gas on the other. In oil-free media, only foam films exist, and gas blockage is easily obtained with many surfactants. But as soon as even a little oil is added to an oil sensitive gas blocking foam, we have seen the gas blockage disappear completely, foam often literally running out of the pack, notable not being destroyed as bulk foam, only losing its ability to block gas in the pores (my note: It is destroyed in the pack, only snap-off occurs at the outlet). Encountering a residual oil droplet in a pore makes a large difference for a foam lamela stabilized by a conventional surfactant, because the surfactant's hydrocarbon tails are solubilized into the oil, making one side of the film different from and, in a porous media, "mechanically strained" with respect to the other side, whose surfactant tails cannot be appreciably solubilized into the gas phase. Therefore, the pseudoemulsion films are more prone to breaking than the foam films. (The situation in a bulk foam is somewhat different, because foam and oil are not "forced" to stay in contact as they are in a pore. Now consider fluorinated alkyl chains which can be described as being oleophobic as well as hydrophobic. Much less of a change is therefore expected for a fluorosurfactant foam film when it contacts a droplet of residula oil and becomes a pseudoemulsion film. To a first approximation it behaves essentially like a soap film.

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Lee, H.O., Heller, J.P., and Hoefer, A.M.W., "Change in Apparent Viscosity of CO2 Foam With Rock Permeability", SPE/DOE 20194 April 1990

Conclusions: 1) The apparent viscosity of CO2 foam in reservoir rock is dependent not only on surfactant type, concentration, and 'quality'(volumetric flowing fraction of CO2), but also to a minor extent on the flow rate and to a large extent on the permeability of the rock sample. 2) The dependence of the apparent viscosity of foam on rock permeability is such that the apparent viscosity is greater in rocks of higher permeability. 3) The dependence of the apparent viscosity of foam on rock permeability is nonlinear, and approaches asymptotic values at both high and low rock permeabilities.

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Fisher, A.W., Foulser, R.W.S., and Goodyear, S.G., "Mathematical Modeling of Foam Flooding", SPE/DOE 20195

Two and three phase steady-state foam mobility models have been developed which exploit the dominant role of the foam coalescence mechanism. These models are base on published data.

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Hudgins, D.A., and Chung, T-H., "Long Distanse Propagation of Foams", SPE/DOE 20196 April 1990

A 1D physical model consisting of a 30 ft long sand packed slim tube was used. All experiments were conducted at 2000 psig backpressure and 150 F. The surfactant was Alipal CD-128(1.0 wt%), and the gas was nitrogen.

A slim tube was waterflooded from an initial oil saturation of 81% to a residual oil of 24%. A similar scheme(as for a previous case with more oil) of trying two different 0.1 PV slugs of foamer, each followed by continuous injection of nitrogen, also failed to generate a foam. Only after injection of a third and larger 1.3 PV slug of foamer followed by nitrogen was any foam generated. Yet, foam was only generated in the last 10 ft section of the tube, and no additional oil was produced. Interestingly, bottle shaking tests by had produced foam in the presence of the same oil using a 1:1 oil-to foamer ratio with ambient air as the gas. One possible explanation for why foam occured only in the outlet section was slightly varyibng backpressue causing flow rate surges above a minimum gas flow rate necessary for foam generation.

Attempts to generate foam in cores (no oil) using 20 in long unfired Beria sandstone cores, with perm of 280 md was not succesful. One possible explanation for the lack of foaming is that the greater surfactant adsorption onto the unfired sandstone core, as compared to the very low adsorption onto the clean silica sand in the slim tube, prevented foaming,also the flow rates in the core were lower and may have been below some threshold velocity.

Conclusions: 1) WAG injection strategy has a great impact upon foam performance; injection of large water slugs can destroy the generated foam. Optimum foam performance can be obtained by adequatly adjusting the WAG ratio and injection sequence. 2) In the absence of oil, foam can propagate in a one-dimensional unconsolidated sandpack for a great distance. 3) The presence of crude oil, even at low oil saturation, is detrimental to faom formation and can sometimes prevent it. Foam was generated, however, under certain conditions of low oil saturation.

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Schramm, L.L., Turta, A.T., and Novosad, J.J., "Microvisual and Coreflood Studies of Foam Interactions With a Light Crude Oil", SPE/DOE 20197 April 1990

In this work, micro-visual observations were made to focus attention on the lamella-oil interactions between a light crde oild and commercial surfactants being considered for foam flooding application in Alberta. Conclu: The mechanism of foam destruction by oil in the system investigated appear to involve first emulsification of oil into droplets that can travel into the interior foam structiur, and subsequently "entering" by which the oil drops penetrate the aqueous/gas interface, disrupting the integrity of the foam lamellae surface.

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Mohammadi, S.S., and Tenzer, J.R., "Steam-Foam Pilit Project at Dome-Tumbador Midway Sunset Field: Part 2", SPE/DOE 20201 April 1990

Concl: 1) Incremental oil due to foam was observed in pilot and first-line peripheral wells. For the pilot, it was 6.0% OOIP. 2) The rate of foam propagation in Midway-Sunset field was

4.5 times that of Kern River field. 3) A reduction in surfactant concentration resulted in a decrease in foam stability and the heat content of the effected zones.

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Llave, F.M., Chung F.T-H., Louvier, R.W., and Hudgins D.A., "Foams as Mobility Control Agents for Oil Recovery by Gas Displacement", SPE/DOE 20245 April 1990

Conclusions: 1) Foam texture is a controlling factor in its rheological behavior. Higher foam qualities resulted in higher measured foam viscosities in smooth capillary tubes and yielded larger foam bubble sizes. A decrease in foam bubble size corresponded with an increase in shear rate. The measured apparent viscosities were not dependent on surfactant concentrations above the CMC of the system but were slightly dependent on system temperature, within the range of conditions and concentrations tested. 2) Fluid injection rates can significantly affect foam behavior. Results showed that the higher injection rates of nitrogen displacing the surfactant solution resulted in foam generation that contributed to a significant increase in sustained pressure gradient across the core, indicative of the generation of foam bubbles. 3) Foams can effectively divert flow of gas from high-permeability, gas-swept zones to low-permeability inadequately swept zones, thereby increasing oil recovery. Foams are more effective in reducing gas mobility and relative permeabiilty in high permeiabilti zones, than in low perm zones. Foam behavoir is highfly dependent upon imposed pressure differential, which itself interacts with and is affected by injection rates, injection sequences, saturations, and flowing pore structure.

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Patzek, T.W., and Koinis, M.T., "Kern River Steam-Foam Pilots", JPT April 1990

Steam foam in both pilots (Kern River and Mecca) was generated by continuous injection of 250 B/D per pattern (cwe) of 50% quality steam with 4wt% NaCl and 0.5 wt% AOS1618 surfactant in the aqueous phase and 0.06 mol% nitrogen in the vapor.

1) Major oil response in both Kern River steam-foam pilots occured after about two years of foam injection. 2) The confined Bishop pilot produced an incremental 8.5% OOIP (5.5% without infill wells) 5 years from the start of foam injection. 3) The unconfined Mecca pilot produced an incremental 14% OOIP 5 years frm the start of foam injection. 4) Foam conveyed some steam along the reservoir bottom, thus improving vertical sweep. 5) The ROS to AOS 1618 foam is the same as that to steam (about 10%). 6) The apparent viscosity of steam foam in the two pilots were similar and decayed from 20 to 60 times as much as steam near the injectors down to steam viscosity at the predicted foam fronts.

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Kuehne, D.L., Ehman, D.I., Emanuel A.S., and Magnani, C.F., "Design and Evaluation of a Nitrogen-Foam Field Trial", JPT April 1990

A surface generated foam was succesfully pumped 9700 ft to the injection interval and propaged into the reservoir. (my comments: they did not experience success)

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Characterization of Steam Foam Surfactants Through One-dimensional Sandpack experiments", Shallcross, Castenier, Brigham, May 1990 Supri TR 73

Both commercially available and experimental surfactants were tested in a one dimensional sandpack under controlled conditions of pressure and temperature. Long chain alpha olefin sulphonate surfactants were found to generate the strongest foams under the conditions examined. Internal Olefin sulphonates, linear toluene sulphonates and linear xylene sulphonate surfactants generated just a strong foams but only at successively higher concentrations. It was found that the strength of the foam produced by a surfactant of a particular chemical structure increased with increasing alkyl chain length. The presence of non-condensable gas increased both the strength and duration of the foam formed. When non-condensable gas is present foam forms and advances ahead of the steam foam, consequently a significant proportion of the increased pressure drop observed across the sandpack is due to the presence of this gas foam rather than just the steam foam.

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de Vries, A.S., and Wit, K., "Rheology of Gas/Water Foam in the Quality Range Relevant to Steam Foam", SPE Res. Eng. May 1990

Experimental results on the rheology of gas/water foam essentially shows that if the gas flow rate is increased at an imposed water rate, the pressure gradient increases, reaches a miximum (the break point), and then decreases. It is postulated that below the break point, foam filled capillaries exist together with water filled capillaries. At the break point, only foam filled capillaries exist, and above the break point, gas filled capillaries appear.

Most investigators(ref Marsden and Khan, Patton and Holbrook) find a decrease in foam mobility when the foam quality in increased for "cold" gas/water foams, whereas others find an increase(ref Heller et al, Minssieux). For steam foam, only an increase in foam mobility with increasing quality has been reported. (Ref Keijzer et al). Faom quality is the volume gas rate in the foam fraction of the total volumetric rate, whereas steam quality is the mass vapor rate in the steam as a fraction of the total mass rate.

Although in steam foam other processes than those in gas/water foam (condensation and evaporation) play a role, we thought that these additional processes should not effect such significatn differences. Consequently, we studied the rheoogy of nitrogen/water foam in porous media, concentrating on a quality range between gas/water foam (qualities normally less than 95%) and steam foam (qualities normally greater than 99%). We show that steam and gas/water foams of comparable foam quality exhibit similar behavior.

Varying the texture of our injected foam by varying the properties of the foam generator did not influence the results within experimental error. We conclude, therefore, that the foam texture is changed by the porous medium to a value independent of the injected texture in such a short distance that the effects are not noticeable in our experiments.

Below the break point, increasing quality decreases the mobility, but above the break poin the opposite is true. We suggest that steam foam is almost always above the break point because of its high quality, where as "cold" foams will normally be below that point.

The mathematical description of the flow of foam through porous media consists of several elements. The basis is formed by a very simplified model of foam flow through a singel capillary. The essential underlying assumptions are that water flows in an annular film around the gas (in the gas, the velocity is constant over a cross section [plug flow]); and that the volume of a lamella and the pressure drop over it are constant. The model predicts that above a certain foam quality lamellae cannot exist in the capillary. To put it differently, foam can exist in a capillary only below a certain quality (the break point) that is a function of the water rate. Their model (fig 6) shows that as gas velocity is increased the quality at which the break occurs decreases -makes sense since at higher rates, the foam degenerates into a MAB mode at a lower quality.

We conclude that foam simulation is possible but requires changing the primary variables from pressure and saturation to gas and water velocities.

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Lee, H.O., and Heller, J.P., "Laboratory Measurements of CO2 Foam Mobility", SPE Res. Eng. May 1990

The effect of surfactant concentration shows that mobility decreases with increasing surfactant concentration regardless of the surfactant type. It also has been shown that as surfactant concentration is increased, the decrease in mobiliity continues well above the CMC of the surfactant solution. The effect of CO2 fraction also demonstrates that mobility can be reduced by increasing the surfactant fraction at constant surfactant concentration. The maximum mobility reduction was observed well above the CMC and at a CO2 flowing fraction of only 60%. The effects of surfactant concentration and CO2 flowing fraction suggest that, for stabilization of foam flow through porous rock, a sufficient quantity of surfactant must be present.

The effect of total velocity on mobility show some shear-thinning behavior under conditions of low surfactant availability. This suggest that under surfactant deficient conditions, the population of lamellae in the pores decreases with increasing flow rate. The effect of rock sample properties illustrates that CO2 foam is not equally effective in all porous media and that, at least for sandstones, the relative reduction in mobility caused by foam is much greater in higher-permeability rock. It seems that by this mechanism, displacement in heterogeneous rocks can be rendered even more uniform than could be expected by the decrease in mobility ratio alone.

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Characterization of Surfactants as Steamflood Additives, MS report Stanford University, Farid Hamida, June 1990

A linear model was used to compare 8 (sulfonates) surfactants using pressure gradient changes and steam mobility reduction as evaluations for foaming. Results indicate that alpha olefin sulfonates (AOS) generate the strongest foam. Flow resistance increased as the alkyl chain length increased. Enrichment in disulfonate content enhanced the propagation speed of the AOS, but reduced its strength. Indications of Nitrogen foam ahead of the steam foam (P and T), support the idea that nitrogen can help stabilize and maintain foam as steam condenses.

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Mixed Surfactant Systems for Enchanced Oil Recovery, Llave, F.M., Gall, B.L., Noll, L.A., December 1990

The results of an evaluation of mixed surfactant systems for enhanced oil recovery are described. The purpose of using mixed surfactants is to allow flexibility in design of surfactant systems that optimize oil production for specific reservoir oil, salinity, and temperature conditions and to determine if the combination of different surfactant types produces synergistic effects compared to the use of surfactant types that have been extensively studied in the past. Ethoxylated anionic surfactants can be used to provide greater salt tolerance for nonethoxylated surfactant such as alkyl aryl sulfonates. An injection strategy which used sodium bicarbonate/sodium carbonate solution as a preflush and in the surfactant slug followd by a salinity gradient was effective in increasing oil production and propagating the mixed surfactant system through a core.

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Morrow, N.R., "Wettability and Its Effect on Oil Recovery", JPT Dec. 1990

Conclusions: 1) Reservoir wettability can cover a wide spectrum of conditions. Systems of intermediate or mixed wettability are quite common, whereas VSWW systems may be a rarity. 2) Adhesion behavoir of crude oil is strongly dependent on pH.

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Friedmann, F., Smith, M.E., Guice, W.R., Gump J.M., and Nelson D.G., "Steam Foam Mechanistic Field Trial in the Midway Sunset Field", SPE 21780 March 1991

Chevron Chaser SD 1020 surfactant was continuously injected with steam and nitrogen for approximately 16 months. Bottomhole injection pressure increased from 100 psig to 300 psig, indicating good foam generation. Better steam distribution across the injectors perforations occured when foam was generated. Improvements in both vertical and areal sweep efficiency of steam were observed.

Both lab and field data were interpreted as evidence that the presence of foam in depth was due to local generatin wherever surfactatn, steam, and nitrogen were present, rather than the propagation of a foam bank generated near the injector.

Conclusions: 1) Faom was generated near the injection well, resulting in a substantial injection pressure increase and a more even steam distribution across the injector's perforatins. However, these effects dissipated rapidly after discontinuing surfactant injection. 2) Faom was generated in depth resulting in the presence of a foam front more than 40 ft away from the injector. The foam front moved at the same rate as the surfactant front. 3) Substantial improvements in both the vertical and areal sweep of the reservoir with steam were observed, which can be directly attributed to the presence of foam in depth.

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Hirasaki, G.J., "Wettability: Fundamentals and Surface Forces", SPE Formation Evaluation June 1991

Force components are electrstatic, van der Waals, and structural. The electrostatic force depends on brine pH and salinity, crude oil composition, and the mineral. The surface forces are expressed as a disjoining pressure isotherm, and its integral is the specific interaction potential isotherm. The specific interaction isotherm can be used to determine the stable and metastable film-thickness profiles at the three-phase contact region for a given capillary pressure and/or curvature of the substrate. This profile gives the contact angle.

The wettability of a rock/brine/oil system cannot be described by a single contact angle because it tis the multitude of contact angles at the various three-phase contact regions in the pore spaces that determines system wettability. (This work focuses on the intermolecular surface forces that affect wettability.)

The intermolecular surface force approach originated with Derjaguin and Landaue's and Verwey and Overbeek's (DLVO) theory of colloidal stability. This theory describes the stability and flocculation of lyophobic (solvent fearing) colloids, considering electrostatic and van der Waals interactions.

The conditions for equilibrium of a system with a pair of interfaces are equality of temperature and chemical potentials between the phases and the augmented Young-Laplace equation.

DISJOINING PRESSURE COMPONENTS:

Van der Waals Interactions: van der Waals forces exist between all matter, and thus, are an important component of the surface forces in thin films. The traditional approach of van der Waals interactions is based on the Hamaker theory, which assumes that the interactions are pair-wise additive and independent of the intervening media and that the interaction between two different media is the geometric mean of the interaction of each medium with itself. The modern approach shows that these assumptions are good if the only interactions are the London dispersion forces (induced dipole/induced dipole) but are not accurate when the Keesom and Debye contributions of polar material are significant.

Electrostatic Interactions: When two charged bodies approach each other in a vacuum, the interactions are governed by Coulomb's law. When the intervening medium is water, the interactions are complicated by the presence of the electrolyte ions. The electrical field near a charged surface decays approximately exponentially with a decay length called the Debye length that is inversely proportional to the square root of the electrolyte concentration. This electrical field, or electrical double layer, extends about 1.0 nm in 0.1 M NaCl. When two charged surfaces approach each other in water, the overlap of the double layers will cause a change in the system energy. The energy differential with respect to the water-film thickness is a force or, expressed per unit area, the electrical contribution to the disjoining pressure.

Structural or Solvation Interactions in Thin Films: The models used to describe the van der Waals and electrostatic interactions treat the bulk and film phases as if they are a continuum with uniform properties up to the interfaces. These models are adequate only as long as the film thickness is large compared with the size of the molecules or any other inhomogeneity on the surface or in the film. We know the center of mass of two molecules cannot coincide, and a large repulsion sets in when the molecular diameter is approached. Also, the molecules on opposite sides of the contact region can arrange to pack efficiently. Thus, to calculate the surface energy or surface tension from the van der Waals model, the interaction potential must be calculated at some cutoff distance that is less than the molecular diameter; e.g., a distance of 0.165 nm has been used for hycrocarbons (ref). If the two bulk phases are separated by a film of another material, the effect of molecular packing becomes important when the film thickness approaches the molecular distances.

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Hornbrook, J.W., "Observation of Foam/Oil Interactions in a New High Resolution Micromodel", SPE 22631 , 1991

A new micromodel construction procedure was developed as a tool to better understand and model pore level events in porous media. The construction procedure allows for almost an exact two-dimensional replication of any porous medium of interest.

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