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Abstract

The use of foam as a mobility control agent shows considerable promise in the development and operation of natural gas storage in aquifers. During gas bubble development, foam is generated in those regions in the reservoir where the gas has most tendency to flow away from the main bubble through permeable streaks and by gravity override, significantly reducing further gas flow. Thus remaining gas injection more uniformly displaces the water and a more confined storage reservoir results. During withdrawal cycles, the entire gas zone can be produced at lower pressures because the reservoir has higher connectivity. There is less base gas trapped, both in the isolated and residual modes. Preliminary studies have established the foam barrier concept to be both economically sound and technically feasible. The current promise shown by foams in enhanced oil recovery will permit considerable technology transfer to their proposed use in gas storage.

I. Introduction

The technology of natural-gas storage underground originated when depleted gas reservoirs, which were producing in the winter, were recharged by pipeline gas in the summer. As the intercontinental pipeline systems spread in the late 1940's, depleted gas reservoirs were developed for full use as underground storage reservoirs. In the late 1950's aquifer storage was developed by forming large gas bubbles in suitable structures filled with water. During the comparatively short withdrawal cycle most of the gas is recovered by expansion from the reservoir to the wellhead pressure, although this behavior may be modified in the presence of an active water drive.

As reviewed by Katz and Tek (1), the major problems facing storage of natural gas in aquifers may be grouped under the following four headings:

1. Long charging times and migration of gas beyond the designated storage volume during the gas injection cycle (approximately 200-260 days/year).
2. Residual gas becoming sealed-off at its prevailing pressure by an active water drive during the gas withdrawal cycle (approximately 120 days/year).
3. The unpredictability of reservoir performance during high withdrawal rates, due to pressure sinks which develop as a result of heterogeneities present in the reservoir.
4. The expense involved in establishing, and the difficulty of recovering the volume of base gas (the total volume of gas stored minus that available for withdrawal).

During the formation of the initial storage volume, some of the injected gas will finger away from the main bubble, sometimes for large distances, because of the adverse mobility ratio between water and gas. Without satisfactorily-placed withdrawal wells to produce from these often thin gas zones, the gas does not depressurize fully during the comparatively rapid withdrawal cycle. It grows in size only as the surrounding water drops to the initial aquifer pressure, and may well then be lost by separating from the main gas body.

When there is a substantial natural water drive, with advancing water sealing off residual gas at its prevailing pressure in the pore space, a considerable fraction of the gas can be separated from the main bubble. In the extreme case it is possible to have interference by water reaching the well-bore towards the end of the withdrawal cycle. The presence of water reduces both the permeability to gas and the bottom-hole pressure drawdown available for gas flow.

The presence of heterogeneities in the reservoir can pose additional problems with gas fingering during the gas injection cycle, sealing off residual gas during the withdrawal cycle, and the formation of pressure sinks during high withdrawal rates. It is extremely important to have all stored gas in responsive communication with the withdrawal wells.

The continued rise in the price of natural gas indicates that the large volumes of base gas required for aquifer storage projects will make the future development of such projects significantly more expensive. Base gas can often account for over 50% of the total gas inventory in aquifer storage schemes (2).

II-1 Gas Storage with Foams

For storage in underground aquifers, natural gas must displace water from the porous medium. Unfortunately, gas does not invade a water-saturated zone in a uniform piston-like fashion. Rather, it overrides and fingers through the water, leading to a very inefficient displacement. This unstable displacement is due to the high mobility (i.e., low viscosity) of gas compared to that of water. It is initiated by macroscopic and microscopic permeability heterogeneities and by gravity.

Figure 1 shows how the adverse gas mobility and density lead to gravity override. The gas preferentially flows near the caprock and in high permeability streaks. Such severe fingering leads to extensive development times for gas-storage reservoirs. More importantly, thin gas zones are produced far from the main gas bubble. During gas withdrawal these far-removed zones can be trapped as off-site and isolated gas which is practically unrecoverable.

Extensive experience in oil recovery practice teaches that stable, efficient displacement requires the mobility of the drive fluid to be equal to, or only slightly less, than that of the displaced fluid. In the case of water displacing a more viscous oil, aqueous polymer solutions are currently employed to achieve "mobility control."

For gas storage reservoirs we propose using a natural gas/water foam as the mobility control agent. Because the foam will contain over 95% by volume of natural gas, it provides a compatible and an easily applied source of mobility control. The major additional cost is that of the surfactant in the water lamellae encompassing the gas bubbles.

A proposed scheme is diagrammed in Figure 2. Note that a typical storage structure is depicted here, but as will be discussed below, an anticlinal structure is actually not needed. A horizontal aquifer could also be used with the following process. First, a pulse of dilute aqueous anionic surfactant, and possibly a polymeric stabilizing solution, is injected into the aquifer. The aquifer may be virgin or it may be an already developed storage reservoir. Along with (or in series) gas is injected to generate in-situ a stable foam of high quality (i.e., the volume of a gas in a unit volume of foam is designated the foam quality). The foam will be generated in those regions of the reservoir where the gas has the most tendency to flow. That is, the foam is placed exactly in those regions which cause the unstable water displacement. Once in place, the foam significantly retards and may even completely block any further gas flow (3,4). Hence, the remaining injected gas is diverted to permit more efficient water displacement and to build a larger gas bubble closer to the injector wells.

Figure 2 shows how foam alleviates the problem of gravity override. The foam is formed in the gas space near the caprock. Remaining gas injection, then, more uniformly displaces the water and a more confined storage reservoir results. There is less likelihood of gas penetrating spillover areas or of forming far-reaching thin gas zones. Also in developed storage reservoirs, it is possible to reconnect previously trapped gas pockets.

During withdrawal cycles the entire gas zone can be produced at lower pressures because the reservoir has higher connectivity. There is less base gas trapped, both in the isolated and residual modes (1,5). Further, if fissures develop in the caprock, the foam has a natural tendency to seal them (6,7). Thus high injection pressures can be maintained with the foam in place.

During production from the central wells, most of the produced gas volume is due to expansion from reservoir to well-head pressures. There need be little movement of the foam once storage capacity is reached. However, during drawdown a pressure gradient develops across the foam zone. Reservoir water attempts to invade the storage region. Foam can support large pressure gradients (6,7,8), but during both depletion and refilling of the gas storage zone some cylic foam movement is to be expected, especially where active water drives are found. This motion, plus natural gravity drainage, leads to foam destabilization and breakage, even with carefully designed stabilizing surfactants. Hence, we anticipate that over long time periods some foam will have to be regenerated to keep the high permeability streaks blocked.

With an active water drive it may be desirable to protect further the gas storage reservoir. This can be achieved with skirt wells surrounding the central injection-production wells, as indicated in Figure 3. At the skirt wells, small volumes of aqueous surfactant and natural gas (or nitrogen) can be injected to generate a foam barrier on an as-needed basis. Because of the ability of foam to withstand large pressure gradients, skirt wells provide a means for isolating the main gas bubble. We create, in effect, an underground storage tank.

Two critical questions arise about a foam-protected, gas-storage reservoir. These are: is it economic, and will it work? To provide definitive answers research is needed on foam generation, flow, and stability in porous media. Section III of this proposal outlines some of the major items that should be investigated. However, it is possible to address these two questions briefly.

Economics

A storage reservoir containing 100 billion SCF of gas could be contained in a reservoir rock of 20% porosity and 20% residual water within a storage cylinder some 1300 m in radius and 50 m average depth. Assuming a formation depth that is compatible with a maximum pressure of 70 atm (~ 1030 psi), it should be possible to reduce the pressure to 20 atm (~ 300 psi) without affecting the foam barrier significantly. This means that some 70 billion SCF could be withdrawn, or approximately a 70% recovery; far more than is typical for underground storage operations. In effect, one has a huge underground tank; this means that, on abandonment, the recovery of residual gas should be much more easily achieved than is the case with present day methods of operation.

The major item of expense will be the cost of the chemical to produce the foam. Using the case of a foam-protected storage reservoir with an active water drive, as depicted in Figure 3, it can be shown that as much as approximately 2.8×10^6 kg of surfactant could be required, assuming a foam of 95% quality and 1% by weight surfactant. At $5.00/kg for the chemical, this amounts to $\$14 \times 10^6$. To account for the cost of the natural gas and nitrogen to form the foam this figure could be increased to $\$23 \times 10^6$. These chemical and gas costs are, at $6.00/MCF for natural gas, approximately 4% of the entire gas inventory. The foam costs are still a very small percentage of those involved in base gas trapped in most storage reservoirs. Preliminary economic feasibility is thus established.

Feasibility

Detailed understanding of foam flow behavior in porous media is not currently available. A considerable body of information is growing, however, because of the promise that foam holds for achieving mobility control in oil recovery processes (3,4,9), notably steam flooding (10,11,12). Foam is in many ways a unique fluid. As discussed below, it achieves low mobility by permeability reduction, not through a viscosity effect.

Foam flows mainly in those channels originally supporting nonwetting, continuous gas phase flow. The permeability to the wetting liquid is not greatly altered. Conversely, in foam flow the permeability to the gas phase is drastically reduced (13,14). Sometimes reductions of 99% or more are reported (3,7,9). Further, some investigators indicate a greater permeability reduction the higher the absolute permeability of the medium (3,13). Thus, foam can minimize, if not eliminate, preferential flow in high permeability streaks, thereby alleviating macroscopic fingering. Also, microscopic fingering is prevented because of the large amount of energy necessary to break the multitudes of individual foam lamellae.

Because of its exceptional flow properties and its cost, foam is currently undergoing extensive field testing in steam flooding. The initial results are very encouraging (11,12). One should bear in mind that steam flooding requires the demanding restriction on foam that it remain stable at high temperatures, and in the presence of oil. Neither of these major deleterious conditions need be present in gas-storage reservoirs. Thus, initial technical feasibility is established for using foam as a protective barrier in gas storage.

II-2 Recovery of Off- Site Trapped Gas

As noted above, foam injection in virgin or partially-developed storage reservoirs should minimize formation of off-site gas in the first place.

The problem of how to recover trapped gas in fully-developed storage reservoirs is not readily addressed. Recovery must occur without interfering with the daily operation of central injection-production wells.

One possible solution is to utilize the skirt wells pictured in Figure 3. Foam can be generated from these skirt wells to encircle a barrier around the major highly gas-saturated storage region. Additional or existing wells outside the skirt area can then be brought on-line to recover off-site gas. The foam should block pressure continuity to the main storage field.

Recovery of down-structure gas, initially trapped because of gravity override and fingering, will be difficult. Production pressures must be controlled so that the foam barrier does not breach and, therefore, production rates will be low. Obviously water-to-gas ratios will also be high. However, recovery of off-site gas is important because of the potential for improving the operation of the substantial number of aquifer gas storage projects in this country.

III Technology Development

Because our understanding of foam behavior in porous media is rudimentary, research is needed to establish the practicality of foam-protected, natural gas-storage reservoirs. In section II the initial feasibility of the scheme has been developed. This section outlines some of the fundamental questions that must be answered before foam barriers can be applied in the field. Three specific areas are addressed below: (a) stabilizing the foam, (b) understanding its flow behavior, and (c) modelling and experimentally verifying the foam barrier concept.

III-1 Foam Stabilizer Design

To be effective the foam must remain stable during the water displacement process while developing the gas-storage reservoir. Thereafter it must remain stable in the presence of ground-water encroachment over very long periods of time. Hence, the choice of stabilizing chemicals is of fundamental importance. They must be cheap, nontoxic, resistant to loss, and most importantly, they must impart tremendous stability to the foam.

Static foams break by two mechanisms (15,16). First, due to the high pressure (i.e., chemical potential) of the gas in the foam, bubbles burst by diffusive gas loss. Second, because of buoyancy, liquid in the individual lamellae drains downward through channels in the foam (known as plateau borders). When an individual lamella is sufficiently thin (e.g., less than 1000 Å) ever-present local instabilities lead to film rupture. Dynamic foams suffer from the same two breakage mechanisms, but in addition the individual lamellae squeeze and expand as they traverse the pore bodies and pore constrictions in the formation. It follows that stability can be established, by slowing gas diffusion loss, by retarding drainage water flow in the lamellae and plateau borders, and by strengthening the liquid films against rupture.

Diffusion loss is slow because of the low solubility of gas in water. However, over long periods of time, there will be a general increase in the bubble size of the foam. Dilute polymers can be employed to increase the aqueous viscosity in the foam films, thereby slowing thinning. Surfactants, because they preferentially adsorb at the liquid-gas interface, can provide a skin which resists rupture. The actual mechanism of rupture stabilization is Gibbs elasticity, or local tension gradients that heal against local thinning.

The task is to find specific surfactant-polymer combinations and concentrations that yield high foam stability. Chemicals that are known to work well are alkyl and aryl sulfonate surfactants and polyacrylamide polymers. To establish stability a dynamic column experiment should be utilized. A bead-pack in a vertical cylindrical column is supplied with methane (or nitrogen and selected mixtures of these gases) bubbling through a porous fritted disk immersed in the aqueous solution of stabilizing agents. The height to which the steady foam column rises in the bead-pack determines the foam life, which is defined as the foam height divided by the superficial gas velocity.

Usually such steady foam lifetime experiments are conducted with empty columns. The bead-pack, however, is more realistic because the glass beads will alter the configuration of the interconnecting plateau borders. We stress, however, that the column tests can be used only for comparative purposes. They will not reflect the exact behavior of the foam in a real porous medium. The experiments outlined below in Section III-3 indicate how the most promising stabilizing agent packages can be evaluated in a flowing situation.

Even if a surfactant-polymer package is found to yield very stable foams, consideration must be given to whether the particular chemicals will withstand the loss mechanisms present in the actual porous medium. Loss can occur by adsorption on rock mineral surfaces, trapping in the isolated water pockets (such as residual, pendular-ring water), and precipitation with hardness ions. Each proposed aquifer must be carefully evaluated for its mineralogy and water hardness content.

Anionic surfactants and polymers are to be preferred because they minimize adsorption loss on normally negatively-charged minerals, especially clays. Little can be done about chemical loss to residual water. Chelating agents are a possibility, but they generally are expensive.

III-2 Foam Generation and Flow

A critical question that must be addressed is how the foam is generated in the porous medium and how it actually flows. Without a detailed understanding of foam flow, we cannot provide definitive answers to questions of how large the surfactant pulse must be, how fast can the storage reservoir be developed under available pressure energy, can the foam be driven intact large enough distances, and will the pressure of the skirt-well foam banks isolate the stored gas from natural water drive? Well defined experiments and theory must be focused on the mechanisms of foam flow in porous media. The present literature on the subject is uncertain and often contradictory.

Apparently foams are generated in porous media by a snap-off mechanism (17,18). Water containing stabilizing chemicals accumulates in the residual, pendular-ring configuration filling small pore necks. As gas flows into the pore constriction and emerges, it tends to snap-off and repeatedly generate foam bubbles. The mechanism is much the same as that of producing bubbles from the tip of a small capillary. Bubble size is determined by the viscosity of the gas and liquid phases, the surface tension, the geometry of the pore spaces, and the flow rate. Hence, in a given porous medium each combination of stabilizing chemicals, and gas and liquid flow rates will produce its own characteristic foam. The governing principles for generating foams of the desired type (e.g., with a specific bubble size and quality) are not known. It follows that foams to be studied should be generated within the actual porous medium, and not external to the pore structure.

Foam flow in a porous medium is also not well understood, but some physical views of the process have emerged (3,4,8,9,13). Foam flows mainly in those channels normally occupied by continuous gas. The wetting liquid remains in the small pores, because of the preferential capillary forces. Thus, to a first approximation, the liquid relative permeability at a given saturation is the same as that for two-phase, gas-liquid flow.

The permeability to the gas in foam flow is drastically reduced, sometimes by a factor of one hundred over that for continuous gas. Gas permeability may even be reduced to zero. One pictures the individual gas bubbles squeezing and expanding through the pore constriction. With large numbers of lamellae, the resistance to squeezing and expansion can become quite large. There is also some breakage of the foam and regeneration during the flow process (13).

We plan steady, column flow experiments. Pressure drops, flow rates, and inlet and outlet bubble sizes will be determined. Tracers such as tritium for the liquid and sulfur hexafluoride or freon for the gas in the foam, will be employed to characterize the residence time distributions in each phase. A microwave monitoring system, referred to below in Section III-3, will provide information on saturation and saturation distribution in the test column.

Our goal is to devise an accurate mathematical model for the foam flow process. Such a tool is sorely needed to answer the questions posed at the beginning of this section, and to permit design of the foam protective barrier shown in Figures 2 and 3.

III-3 Experimental and Mathematical Simulation

Experimental techniques will be employed to establish the long-term stability of foam for aqueous solutions of different stabilizing agents in the presence of nitrogen or methane (and selected mixtures of these gases), and to evaluate the flow properties of foam incorporating the most promising stabilizing packages. As noted and described above in Section III-1, a dynamic column experiment will be employed to establish foam stability.

The generation and flow properties of foam will be studied in experiments on parallel-sided slabs of porous material in the form of a quadrant of a 5-spot injection pattern, as illustrated in Figure 4. These columns will be arranged so that the parallel sides are either horizontal or vertical; in the latter case the effect of gravity override will be studied.

As discussed above in Section III-2, tracers in the liquid and gas will be used to characterize the residence time distributions in each phase. A microwave monitoring system, operating across the parallel sides of the column, will be developed to determine the liquid saturation and saturation distribution throughout the column. Microwave techniques have been successfully employed in a number of fields in the physical sciences and engineering for determining the water saturation in porous media.

Finally, the results of the experimental programs described above will be incorporated in a mathematical model for the foam generation, stabilization, and flow processes.

IV Conclusions

It is concluded that natural gas storage with foam as a mobility control agent during the development and operation of the gas storage reservoir shows considerable promise. Preliminary studies have established it to be both economically sound and technically feasible.

Specific areas requiring study for further development of the technology are those involving (a) long-term foam stability, (b) generation and flow behavior of foam, and (c) model and experimental verification of the foam barrier concept.

The current promise shown by foams in enhanced oil recovery will permit considerable technology transfer to their proposed use in gas storage.

Acknowledgments

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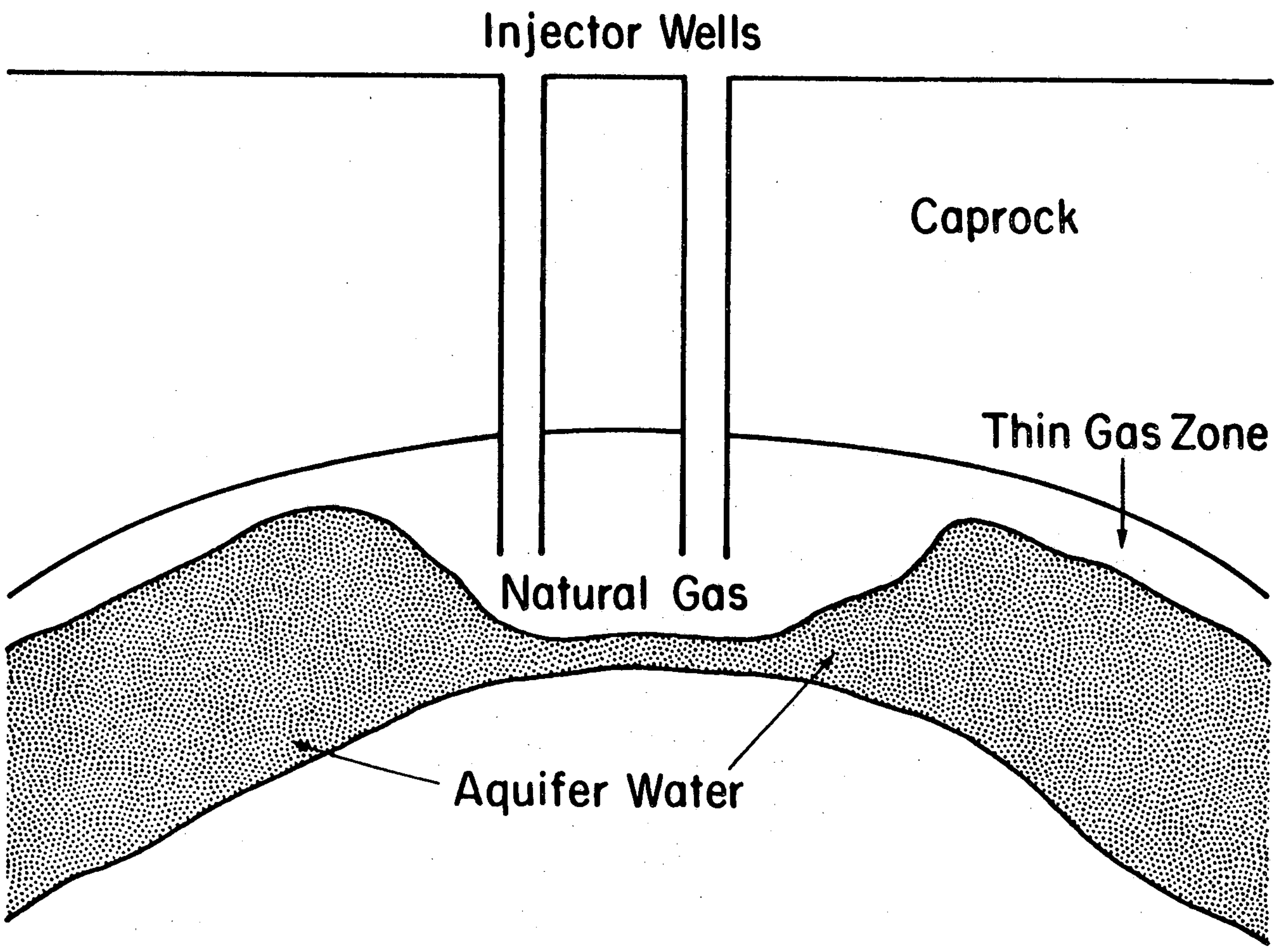

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Figure 1. Adverse gas mobility and density leading to gravity override.

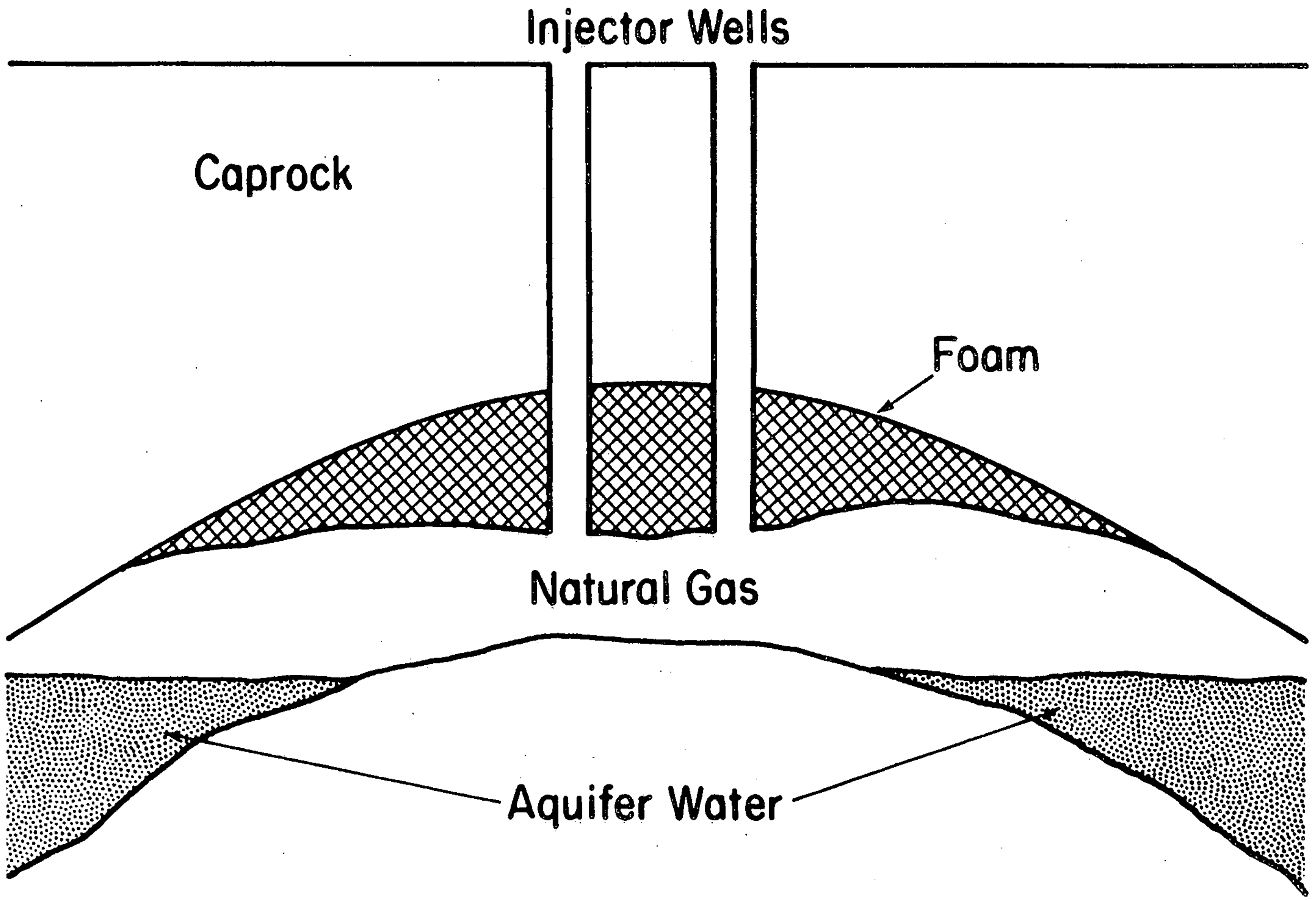

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Figure 2. Gravity override alleviated by foam.

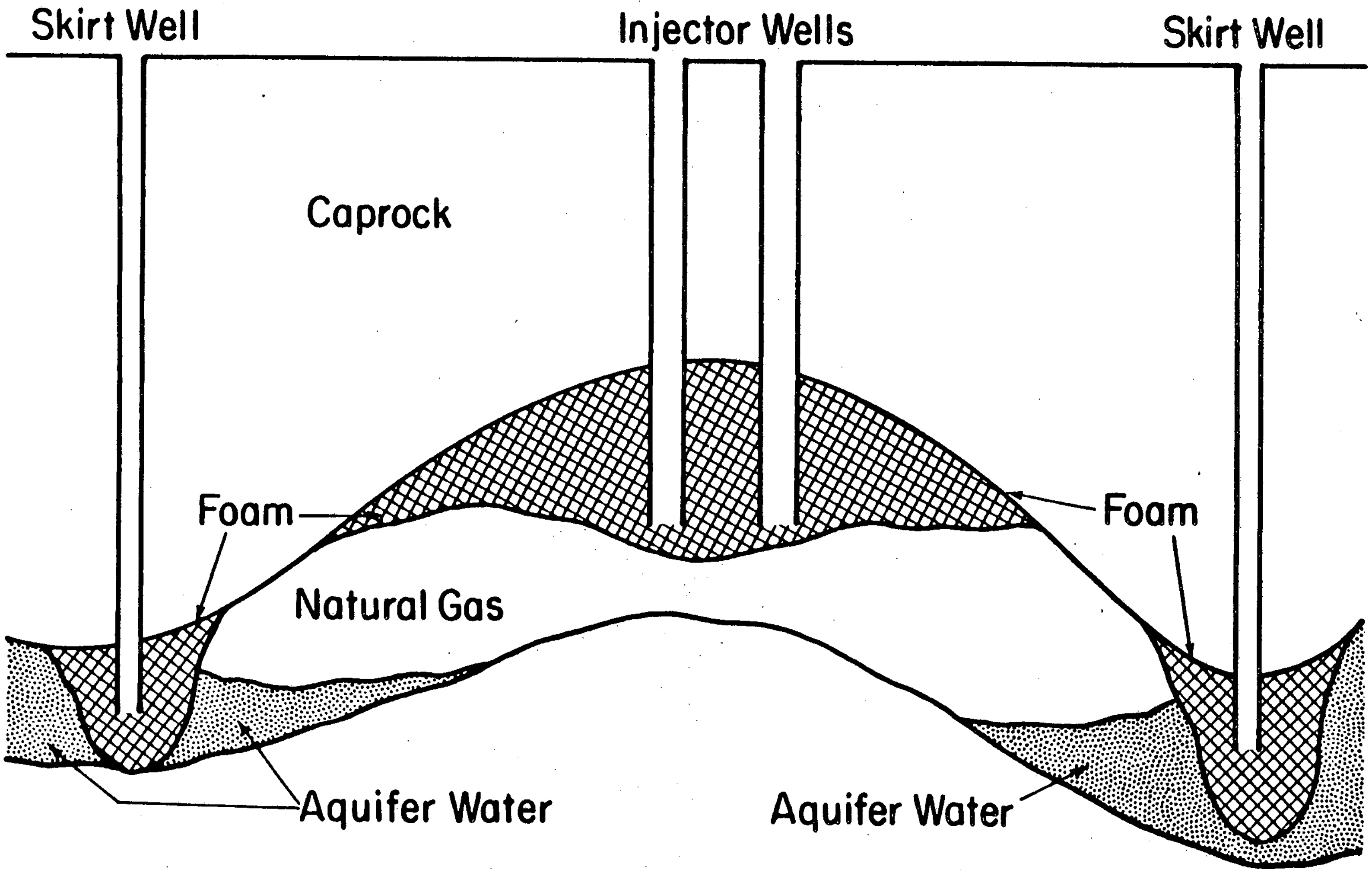

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Figure 3. Further protection in presence of active water drive afforded by foam injected from skirt wells.

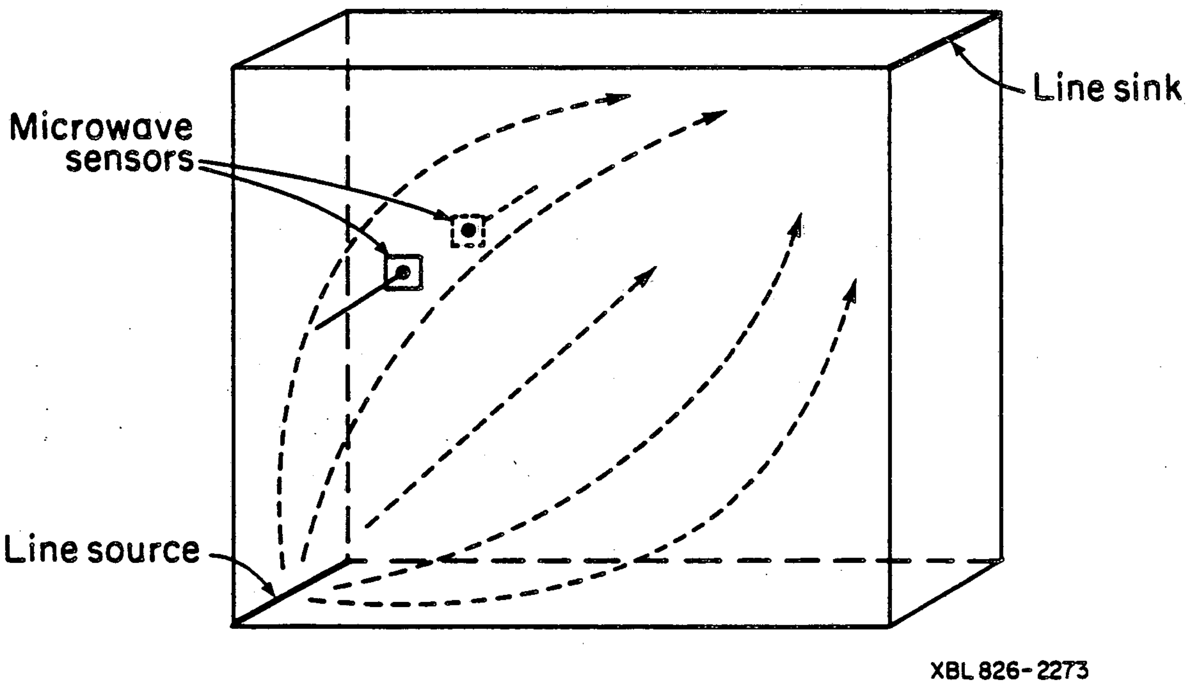

Figure 4. Experimental plan for investigation of vertical or horizontal movement of foam in a porous medium.

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