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LABORATORY AND FIELD EVALUATION OF POLYURETHANE FOAM FOR LOST CIRCULATION CONTROL *

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ABSTRACT

A two-part polyurethane foam has been tested in the laboratory and in the field to assess its utility in controlling lost circulation encountered when drilling geothermal wells. A field test was conducted in The Geysers in January, 1988, to evaluate the chemical formulation and downhole tool used to deploy the chemicals. Although the tool apparently functioned properly in the field test, the chemicals failed to expand sufficiently downhole, instead forming a dense polymer that may be ineffective in sealing loss zones. Subsequent laboratory tests conducted under simulated downhole conditions indicate that the foam chemicals undergo severe mixing with water in the wellbore, which disturbs the kinetics of the chemical reaction more than was previously contemplated. The results indicate that without significant changes in the foam chemical formulation or delivery technique, the foam system will be ineffective in lost circulation control except under very favorable conditions.

INTRODUCTION

In a cooperative effort between the geothermal drilling industry and the US Department of Energy, the potential for using a two-component polyurethane foam for lost circulation control has been investigated with laboratory and field testing. Although the results indicate that the foam chemical formulations currently available are of limited use for lost circulation control, there may be other applications where they can be used beneficially. This paper thus presents the results of the laboratory and field tests and discusses the utility of the foam in the downhole environment.

EARLY LABORATORY TESTS

In 1980, with Department of Energy (DOE) funding, Sandia National Laboratories contracted with Southwest Research Institute (SwRI) to test a two-component polyurethane foam formulation supplied by Poly Plug, Inc., at elevated pressures and temperatures. According to the supplier, the Poly Plug formulation was designed to expand appreciably and remain stable under downhole conditions. The testing was done at SwRI because of the existence of SwRI's Deep Ocean Simulator. This facility employed a 3750-psi (48-inch-diameter, 133-inch-long) pressure vessel capable of operating at temperatures up to 300°F.

Three two-compartment hydraulic cylinders were filled with 15 lb of the two components of the foam formulation and placed inside the test vessel. The test vessel was partially filled with water and closed before pressurizing to 900 psig with nitrogen. Electrical strip heaters were used to heat the ambient fluid to a selected temperature. Temperatures of 100, 200, 250, and 300°F were used in the various tests.

When the test conditions had stabilized, pressurized nitrogen was discharged through the pressure vessel lid into the first cylinder, thereby discharging the chemicals through a static mixer and into a canvas bag designed to contain the foam. Conditions were held for fifteen minutes, then the pressure was reduced to 600 psig and the second cylinder was discharged into a second canvas bag. The procedure was repeated for 300 psig.

Pertinent results obtained in the SwRI tests are summarized in Table 1 on the next page. Other results not listed here are presented in Tschoepe (1982). The listed foam densities indicate that the Poly Plug foam formulation is capable of undergoing significant expansion at elevated pressures and temperatures. Densities from 8.1 to 18.3 lb/ft^3 were measured in the 900 psig tests, compared with a water density of 62.4 lb/ft^3 and an initial liquid chemical density of 75 lb/ft^3; thus the chemicals expanded 4 to 9 times their original volume at 900 psi. The compressive strengths of the foam samples ranged from 150 to 300 psi. Fluid-loss test results indicate that the foam samples had very low permeabilities.

Based on these results, it was concluded that the Poly Plug foam formulations may produce a suitable downhole material for lost circulation control in geothermal drilling.

PROTOTYPE TOOL DEMONSTRATION

The principals of Poly Plug were granted a patent in March, 1980, for a self-contained device

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TABLE I

SwRI LABORATORY TEST RESULTS

	TEST CONDITIONS		MEASURED PARAMETERS					CALCULATED
TEST[1] NO.	AMBIENT FLUID PRESSURE (psig)	AMBIENT FLUID TEMPERATURE (°F)	MAXIMUM EXOTHERM TEMPERATURE (°F)	DENSITY[2] (lb/ft^3)	CLOSED CELL FRACTION	COMPRESSIVE STRENGTH AT 200°F (psi)	4-HR FLUID LOSS 100 psi (ml)	SPECIFIC[3] GAS PRODUCTION (lb/lb)
SWR1	0	104	222	7.4	0.47	175	55	0.010
SWR2	300	100	165	17.7	0.72	285	104	0.082
SWR3	900	102	142	18.3	0.62	295	72	0.205
SWR4	300	202	342	13.6	0.64	230	77	0.088
SWR5	600	201	355	9.7	0.53	215	60	0.217
SWR6	900	202	365	9.4	0.66	205	77	0.297
SWR7	300	250	378	7.9	0.64	195	73	0.148
SWR8	600	250	347	9.1	0.76	210	64	0.232
SWR9	900	249	400	8.6	0.57	180	48	0.310
SWR10	300	299	562	9.9	0.63	290	63	0.100
SWR11	600	300	314	11.2	0.78	270	29	0.198
SWR12	900	302	308	8.1	0.72	285	22	0.350

Notes:

1. SWR = Southwest Research test.
2. Density ρ_f measured at atmospheric pressure.
3. Calculated with Eq. 1, assuming T = maximum exotherm temperature (°R).
4. Chemical batch size = 15 lb.
5. Atmospheric pressure = 14 psia.
6. Chemicals heated to same temperature as ambient fluid prior to injection.
7. All tests reported here used chemical forumla No. 3 (see Tschoepe, 1982).

for deploying and mixing the constituents of a polymeric foam system downhole (Baughman and Doyle, 1980). Poly Plug designed a tool based on this patent that could be lowered downhole on a drill string and activated using the surface mud pumps. A schematic of one of the tool designs is shown in Figure 1.

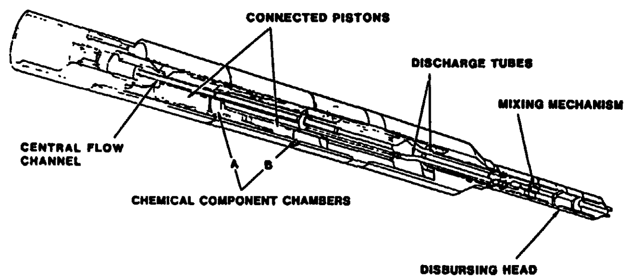

Figure 1. Schematic of Poly Plug polyurethane foam tool.

In the spring of 1984, a demonstration of the operation of the prototype tool was conducted at Sandia in cooperation with Poly Plug and NL Baroid (Polk et al, 1985). A simulation of a wellbore in a lost circulation zone was built above ground to facilitate post-mortem analysis and documentation. A twenty-foot-long, six-inch-diamter pipe, which represented the wellbore, contained a section of expanded metal near its base to simulate the loss zone. A three-foot-diameter cardboard form tube was installed around the simulated wellbore, loaded with seven tons of 3/4 to 1-1/2 inch river gravel, and filled with water to simulate the formation in the loss zone.

The tool was hung above the simulated wellbore and activated using pressurized nitrogen. A total of 110 lb of foam chemicals was mixed and injected into the simulated wellbore, where it reacted and expanded into the gravel bed. After a 30-minute cure period, the cardboard tube was cut away to reveal the consolidated gravel mass seen in Figure 2. It was concluded that the tool successfully mixed and delivered the foam chemicals in this atmospheric-pressure test. Measured foam properties were similar to those measured in the SwRI tests conducted under atmospheric conditions.

Figure 2. Gravel mass consolidated by foam in prototype tool demonstration.

GEOTHERMAL DRILLING ORGANIZATION FIELD TEST

In February, 1987, an agreement was signed among members of the Geothermal Drilling Organization (GDO) and others to field test the Poly Plug foam formulation and downhole tool. Participants in the project were:

- H & H Tool Co.;
- Grace Drilling Co.;
- Unocal, Geothermal Division;
- Geothermal Resources International;
- Sandia National Laboratories for DOE; and
- Baroid, NL Industries.

Baroid acted as the contractor to DOE to furnish the DOE share of materials and field services. H & H Tool Co. moved the materials to and from the drilling site, provided the container building in which the tools were stored and prepared for use, and provided other equipment needed to support the tests. Rig time and use of the wellbore was to be provided by the operators, Unocal Geothermal and Geothermal Resources International, and by the rig owner, Grace Drilling Co. Poly Plug provided technical support and directed the application of the tool. Sandia supported the tests with the necessary field instrumentation to facilitate evaluation of the tool performance.

The GDO-sponsored field test was conducted in the Geysers, January 19-22, 1988, in Unocal

Geothermal well OF51-11. Although lost circulation was not encountered as anticipated in the 2500-3100 ft level, the decision was made to discharge the tool in the open hole to evaluate the function of the tool and to determine the potential for using the rigid foam as a bridge plug. After the first run was aborted because a screen had been inadvertently left in the drill string following a turbo-drilling run, a second run was successfully completed. The test was run in a 10-5/8 inch section of open hole, 87 ft long, that was drilled below the final casing shoe to a depth of 3222 ft. Because of the limited extent of open (uncased) hole available and the large foam expansion considered possible, only one-half of the tool's 40-gallon chemical capacity was utilized. The tool was lowered to a depth of 3191 ft and was discharged according to procedure.

Three stands of drill pipe were then pulled, and the 30-minute wait time for the foam to cure was observed. The tool was then lowered in an attempt to locate the top of the foam plug. At 3193 ft, the hook weight indicator dropped 5000 lb, suggesting that the top of the foam plug had been located. The tool was tripped out, and a junk basket was lowered to the bottom of the hole without finding the foam plug. Upon resumption of drilling, several pieces of brittle polymer were washed out of the hole and recovered at the mud pit. Densities of 35.0 and 37.4 lb/ft^3 were measured with two of the samples, indicating that the foam chemicals approximately doubled in volume under the imposed downhole conditions. This was considered a relatively small expansion, compared with the 4-9-fold expansion reported in the SwRI tests at 900 psi.

Examination of the recovered samples and the lack of hole fill indicated that the foam chemicals did not conglomerate together to form a plug before solidifying, even though the tool apparently functioned as intended. Two possible causes were considered likely. First, the calculated bottomhole pressure of the completely filled wellbore was 1485 psig. This was considerably higher than the maximum 900 psi of the SwRI laboratory tests. Secondly, the mixed chemicals were injected into drilling mud in the field test, whereas the foam chemicals were generated in an inert environment inside canvas bags in the SwRI tests. Because of the uncertainties associated with the field results, it was determined that further laboratory testing under more controlled conditions was necessary before conducting further field trials.

LABORATORY TESTS UNDER DOWNHOLE CONDITIONS

Foam Test Facility Design

It was decided that Sandia would attempt to resolve some of the uncertainties associated with the field results by building a laboratory facility in which all pertinent downhole conditions could be simulated. Beginning in February, 1988, the Foam Test Facility was designed and constructed. A photograph of the facility is shown in Figure 3.

Figure 3. Photograph of Sandia's Foam Test Facility.

A test section consisting of 3-inch or 6-inch (schedule 160) seamless pipe is pressurized to levels as high as 2300 psi using a hydraulic intensifier. Thermostatically controlled band heaters are used to heat the test section and enclosed fluid to temperatures as high as 300°F.

The foam chemicals are injected using a second hydraulic intensifier in which two separate cylinders are stroked in parallel to inject the chemical A and B components. The chemical cylinders and flow lines are heated to a temperature near the test section temperature prior to injection. The two component fluid streams are combined to a single stream and flow through a static mixer located inside the test section.

Instrumentation in the Foam Test Facility includes: pressure transducers to measure the test section pressure, chemical injection pressure, and hydraulic system pressures; thermocouples to measure the chemical exotherm temperature, test section temperature, and chemical temperatures; and linear displacement transducers to measure the stroke of the hydraulic cylinders. This instrumentation was interfaced with a PDP-11 computer for sampling and recording the real-time data as well as providing control of several system functions during and after foam injection. A complete description of the facility is provided in Loeppke et al (1989).

High-Pressure, High-Temperature Test Results

Starting in March, 1988, twelve tests were run in the Foam Test Facility under various conditions in an attempt to determine the cause of the foam's failure to expand sufficiently and form a plug in the Geysers field test. Ambient pressures in the lab tests ranged from atmospheric to 930 psig; ambient fluid temperatures ranged from 155 to 290°F. Both drilling mud from the Geysers field test and water were used as the ambient fluid. In most tests, chemicals from the drums onsite at the field test were used; however, alternate chemical formulations were also tested in an attempt to improve the results.

The results of these tests are summarized in Table 2, together with the results from the Geysers field test. A general observation is that the effects of ambient pressure were dramatically more pronounced in the Sandia tests than they were in the SwRI tests, but the Sandia results are consistent with the results of the Geysers field test. Very little foam expansion was experienced at elevated pressures. At approximately 900 psi, for example, the foam densities in the Sandia tests ranged from 34 to 49.3 lb/ft^3, compared with 8.1 to 18.3 lb/ft^3 in the SwRI tests under similar pressures and temperatures.

The effects of drilling mud on foam expansion were found to be minor, but mud was found to have a significant effect on the structure of the resulting polymer. Foam samples generated in drilling mud from the Geysers field test were noticeably structurally weaker.

Another observation made during these tests was that in most cases, the liquid chemical sank to the bottom of the test section (or basket used to contain the chemical) before substantial foaming occurred. This is significant because it would allow the liquid chemical to sink to the bottom of the wellbore or into the loss zone, where it would tend to remain after it expands.

TABLE 2

GEYSERS FIELD TEST AND
SANDIA FOAM TEST FACILITY RESULTS

	TEST CONDITIONS					MEASURED PARAMETERS			CALCULATED	
TEST[1] NO.	AMBIENT FLUID	AMBIENT FLUID PRESSURE (psig)	AMBIENT FLUID TEMPERATURE (°F)	INITIAL CHEMICAL TEMPERATURE (°F)	CHEMICAL BATCH SIZE (lb)	MAXIMUM EXOTHERM TEMPERATURE (°F)	RECOVERED FOAM MASS (gm)	DENSITY[2] (lb/ft^3)	SPECIFIC[3] GAS PRODUCTION (lb/lb)	REMARKS
GFT1	mud	1500	185	185	198	---	--	37.7	0.0849	Light-colored specimen.
							--	35.4	0.0961	Dark-colored specimen.
FTF1	mud	930	195	180	1.0	---	52	41.5	0.0443	Same mud as in the Geysers field test.
FTF2	water	930	200	205	1.0	---	327	45.1	0.0355	Largest specimen.
								34.0	0.0676	Second largest specimen.
								49.3	0.0268	Dribble.
FTF3	water	340	200	185	2.0	323	690	45.0	0.0138	From screen sample, 1st chemical injection.
								29.8	0.0337	Bottom specimen, 2nd chemical injection.
								20.6	0.0588	Dribble, 2nd chemical injection.
										2-lb of chemical injected in two separate masses, 1 lb each.
FTF4	water	700	220	195	2.0	334	672	46.1	0.0253	From screen sample.
								33.1	0.0542	Dribble.
FTF5	water	7	195	75	0.7	---	174	10.6	0.0078	Sample from bend in top of test section.
								11.1	0.0074	Sample from top horizontal pipe of test section.
										Top valve left open to discharge pressure.
FTF6	water	0	200	75	0.6	---	81	4.32	0.0133	Chemicals discharged into bucket rather than test section.
FTF7	water	167	210	200	1.0	356	357	13.8	0.0497	From screen sample.
								15.7	0.0423	Dribble.
										Chemicals jetted vertically in test section rather than through 90° bend against test section wall (as in all other tests).
FTF8	water	364	290	300	1.0	325	265	24.0	0.0505	From screen sample.
								15.3	0.0906	Dribble.
FTF9	---	---	---	---	---	---	---	----	----	Equipment failure--relief valve opened prematurely.
FTF10	water	365	275	190	2.0	---	614	40.4	0.0199	Component A with higher concentration of accelerator. Component B same as in the Geysers field test.
FTF11	water	297	230	230	2.0	349	734	51.2	0.0076	Same chemicals as in the Geysers field test.
FTF12	water	292	155	155	3.0	299	659	29.0	0.0315	Component A same as in the Geysers field test. Component B with higher concentration of catalyst (i.e., low-temperature formula).

Notes:

1. GFT = Geysers Field Test; FTF = Foam Test Facility test.
2. ρ_f values reported are dry densities, converted from measured saturated densities (see Loeppke et al. 1989).
3. Calculated with Eq. 1, assuming T = max. exotherm temp. or 330°F (790°R) when not measured.
4. Atmospheric pressure = 12 psia, except for GFT1 (15 psia).
5. High-temperature chemicals from the drums onsite at the Geysers field test used, unless otherwise noted.
6. FTF1-FTF8 used the 3-inch test section; all others used the 6-inch test section.
7. FTF3-FTF5 and FTF7-FTF8 used a cloth-covered screen mesh below the foam injection port to catch the chemical mix.
8. FTF1-FTF10 used two 1/4-inch ID X 7-inch long static mixers in series; FTF11 used one 1/8-inch ID X 5.5-inch-long static mixer; FTF12 used two 1/8-inch mixers in series.

In the case where drilling mud was used as the ambient fluid, however, the evidence indicates that foaming began immediately as the chemical exited the static mixer port. In this case, the chemical may simply stick to the wellbore wall or float upward when foaming begins, as it apparently did in the Geysers test. Drilling mud additives may, therefore, cause foam emplacement problems during field application in addition to reduced structural strength of the solid polymer.

Several changes to the test facility and procedures were made during the foam facility test series to determine whether the test conditions imposed by the facility had any effect on the quality of the foam generated. These changes included: improvements to the pressure maintenance system to maintain a more constant ambient pressure during and after chemical injection; addition of a wire basket to catch the chemical near the injection port to prevent dispersal in the ambient fluid; and changes in the chemical injection hardware and procedure to ensure thorough mixing and proportioning of the chemical components. None of these changes was found to have any significant effect.

In a final attempt to improve the test results, the chemical formulation was changed in the last two tests. At the suggestion of Poly Plug, a higher concentration of accelerator was added to Component A in test FTF11, and a higher concentration of catalyst was added to Component B in test FTF12. These changes, however, were not successful in improving the expansion of the foam under elevated pressures. Having exhausted all apparent options for improving the results, testing in the Foam Test Facility was terminated in May, 1988.

ANALYSIS

Specific Gas Production

Upon mixing the two components of the foam chemicals, the chemicals react to produce CO_2 gas. Part of the CO_2 is dissolved into the solid polymer and/or ambient fluid. The rest of the CO_2 resides in the pore space of the expanded foam as a free gas, thus resulting in a reduced density of the foam compared with that in its liquid state prior to the reaction. A model is developed in Loeppke el al (1989) for describing the expansion characteristics of the the foam in terms of the mass of free gas generated. This model is based on the ideal gas law and the distribution of pore space among closed and open cells in the foam.

The primary result of the model is an equation for calculating the specific gas production associated with a foam sample generated under controlled conditions:

$$\frac{m_g}{m_c} = \left[\frac{R\ T\ \rho_c}{P\ (\frac{\rho_c}{\rho_f} - 1)} + 1 \right]^{-1} , \qquad (1)$$

where the specific gas production is defined as the ratio, m_g/m_c, of the mass of free CO_2 gas to the mass of the liquid chemical prior to mixing.

Equation 1 was used together with the measured foam densities, ρ_f, measured exotherm temperatures, T, and imposed pressures, P, to calculate the specific gas production for each of the tests conducted at SwRI, at Sandia, and in the Geysers. The results are plotted in Figure 4 as a function of ambient pressure. Note that the mass of free gas generated at atmospheric pressure was very similar in the Sandia and SwRI tests. At elevated pressures, however, the calculated specific gas production in the SwRI tests greatly exceeded that of the Sandia tests, while the Geysers field test results are consistent with the trend of the Sandia test results.

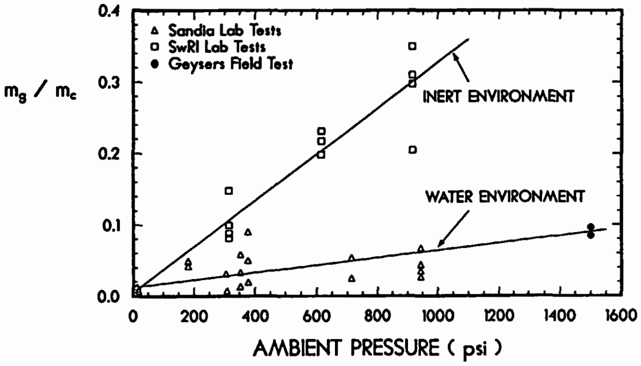

Figure 4. Calculated specific gas production for the Geysers field test, Sandia lab tests, and SwRI lab tests.

The SwRI test results are inconsistent with the starting chemistry of the foam components. Analysis shows that the isocyanate groups in typical polyurethane formulations are capable of generating a maximum specific gas production of only about 0.2. Consequently, it is difficult to explain the magnitude of the SwRI results. The discrepancy may be due to the unique chemical formulation employed by Poly Plug, to experimental error in measuring the SwRI foam densities, or to a slight expansion of the foam when the ambient pressure was reduced during each SwRI test. In any case, barring large experimental errors in the SwRI tests, it is evident that the SwRI tests produced significantly more free CO_2 gas than either the Sandia lab tests or the Geysers field test.

Comparative Analysis

It is reasonable to assume that the large differences in foam expansion between the SwRI tests and the Sandia and Geysers tests are due to differences in the conditions imposed during the various test series. Most test parameters were similar among the various test series and thus can be ruled out as a cause of the differences in results. Other parameters require more careful scrutiny.

An obvious difference between the Sandia and SwRI tests is the chemical batch size used in the tests. In the SwRI tests, 15 lb of chemicals were injected into each canvas bag. The chemicals were held together by the bag, thereby minimizing exothermic heat loss during the chemical reaction and maximizing the potential for an elevated exotherm temperature. In contrast, the chemical batch size used in the Sandia tests ranged from 1 to 3 lb. The chemicals were jetted into the ambient fluid but for the most part conglomerated as a single mass prior to solidifying. Poly Plug expressed the concern that the relatively small chemical batch used in the Sandia tests may have resulted in excessive exothermic heat loss, thereby suppressing gas generation and volumetric expansion of the foam.

This concern, however, is not supported by the experimental data. The chemical exotherm temperatures measured in the Sandia tests ranged from 299 to 356°F. Most exotherm temperatures measured in the SwRI tests ranged from 142 to 378°F, with one test reaching 400°F and another reaching 562°F. Thus the exotherm temperatures were comparable in most Sandia and SwRI tests, even though the chemical batch sizes differed by a factor of 5 to 15. Two conclusions can be drawn from this result: 1) within the range of 1 to 15 lb, the chemical batch size used in a test does not significantly affect the exotherm temperature; and 2) there is no correlation between the exotherm temperature and the volumetric expansion of the foam.

Another major difference in the imposed conditions among the various test series is the potential for the foam chemicals to mix with the ambient fluid. The canvas bags used to receive the chemicals in the SwRI tests were employed for the express purpose of preventing contamination of the foam chemicals with the ambient water in order to "avoid undesirable effects" (Tschoepe, 1982). Although the porous canvas bag contacted the top surface of the water in the test vessel, the foam itself was probably effectively isolated from the water by the canvas. There was certainly very little, if any, jet mixing of the chemicals with the water.

In both the Sandia tests and in the field, however, the chemicals were vigorously mixed with water during injection into the ambient fluid. The chemical jet velocity exiting the 3/8-inch static mixer port in the Geysers field test was approximately 57 ft/sec, while that in the Sandia tests was about 2.5 ft/sec. The corresponding Reynolds numbers for the chemical jets were 905 and 40, assuming 200 cP as a conservatively high estimate of the liquid chemical viscosity at elevated temperatures. The Reynolds number at which a free jet undergoes a transition from laminar to turbulent flow has been shown to range from 0 to 12 (White, 1974); thus free jets are inherently unstable. It can therefore be concluded that the jet velocities in both the Sandia and Geysers tests were sufficient to cause turbulent mixing of the foam chemicals with the ambient fluid.

At atmospheric pressure, the effects of mixing the foam chemicals with water were found to be relatively small, as evidenced by the similarity of the Sandia and SwRI test results at atmospheric pressure. At elevated pressures, however, the solubility of CO_2 gas in water is relatively high. For example, the solubility of CO_2 in water at 900 psia and 122°F is over fifty times the solubility at atmospheric pressure (Perry, 1963; Dean, 1985). It is therefore reasonable to conclude that a significant fraction of the CO_2 gas produced under pressure by the foam chemicals in the presence of water is dissolved into the water and is thus not available to expand the foam. In an inert environment, such as that which existed in the SwRI tests, a larger fraction of the generated CO_2 gas remains as a free gas capable of expanding the foam.

If mixing with the ambient fluid has an important effect on foam expansion, as suggested, then the chemistry of the ambient fluid would also be expected to be an important variable. It has been shown that there is little difference in the volumetric expansion of foam generated in water and that generated in the drilling mud from the Geysers field test. It is thus concluded that the drilling mud used in the field test did not sigificantly affect the specific gas production. The drilling mud did, however, have significant effects on other characteristics of the foam. In the lab tests, the foam was apparently generated at an accelerated rate in the drilling mud, displayed a different color and texture, and was noticeably structurally weaker than foam samples generated in water.

Finally, the viability of the chemical stock used in the field test and in the subsequent Sandia lab tests is a concern. Due to the proprietary nature of the foam chemical formulation, we were not able to independently verify that the SwRI, Geysers, and Sandia tests were run with the same formulation. Two discrepancies between the observations recorded in the SwRI tests and those made during the Sandia lab tests, in fact, suggest that the formulations may have been different:

- The density of the chemicals used in the Sandia tests prior to mixing was measured at 68.3 lb/ft^3. Tschoepe (1982) states that the chemicals used in the SwRI tests had a pre-foam density of 75 lb/ft^3.
- When the chemical cylinders were heated in the Sandia tests, the Component A cylinder pressure invariably increased to a higher level than the Component B cylinder pressure. This indicates that the Component A formulation used in the Sandia tests had a higher vapor pressure at elevated temperatures than Component B. Tschoepe (1982) states that Component B had a higher vapor pressure than the Component A formulation used in the SWRI tests.

Implications for Lost Circulation Control

The existing polyurethane foam system has only a 40-gallon chemical capacity; thus it relies on significant foam expansion to generate the large volume of material needed downhole to plug a typical loss zone. The poor foam expansion found to occur under pressure in the presence of water therefore has implications for the use of the system in treating the severe loss zones for which it was designed.

To explore these implications, an analysis was conducted assuming the ideal foam plug geometry shown in Figure 5. It is assumed that the chemicals are injected and sink to the bottom of the wellbore before expansion begins. As the foam expands, it fills the section of wellbore beneath the loss zone and the wellbore interval in the loss zone before expanding into the loss zone itself. Equations that describe this plug geometry in terms of the loss zone and foam expansion characteristics are derived in Loeppke et al (1989).

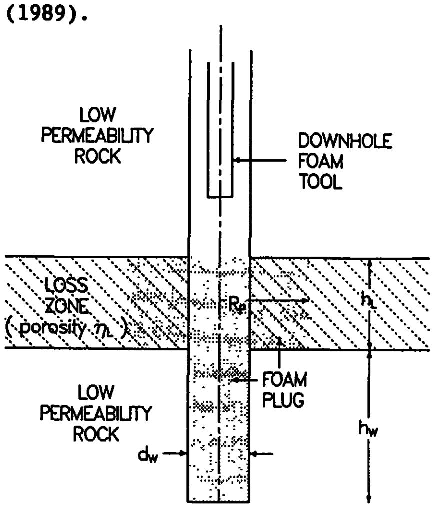

Figure 5. Schematic of typical loss zone and ideal geometry of polyurethane foam plug.

The calculated radius of the ideal foam plug assumed in Figure 5 is plotted in Figure 6 for a 10-5/8 inch wellbore with a downhole pressure of 180 psia. The height of the loss-zone interval is assumed to be 10 ft, and it is assumed that the hole was drilled for another 10 ft below the loss zone to ensure that the entire zone had been penetrated before the foam tool was employed. The family of curves in Figure 6 represents the results for a variety of assumed loss-zone porosities. Note that the curves converge at the maximum usable foam density, which is the density at which the foam fills the wellbore over the loss-zone interval but does not have sufficient volume to penetrate the loss zone itself.

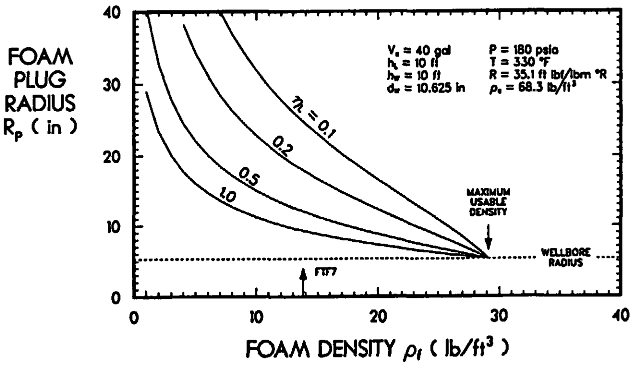

Figure 6. Calculated foam plug radius for the ideal polyurethane foam plug in a loss zone having the specified characteristics.

Shown for reference in Figure 6 is the 13.8 lb/ft^3 density of the foam specimen from Sandia test FTF7 at 179 psia. With loss-zone porosities less than 0.2, foam of this density would extend into the loss zone to a radius of over 17.9 inches under the ideal conditions assumed. This would result in a plug greater than 12 inches thick after the wellbore is re-opened to its original 10-5/8 inch diameter, which should be sufficient to effectively seal the loss zone. A plug with an annular thickness less than 12 inches would result from greater loss-zone porosities, larger wellbore diameters, longer loss-zone intervals, longer wellbore sections below the loss zone, or higher ambient pressures than those assumed here.

In general, it can therefore be concluded that the existing polyurethane foam formulation and downhole tool may be effective in plugging loss zones under low-ambient-pressure conditions if the loss zone is of limited vertical extent, has a relatively low overall porosity, and has a precisely known location.

DISCUSSION

Because of the failure of the two-component foam to expand sufficiently and the limited mass of chemicals available downhole with the current foam tool, the current two-component system is probably not suitable for general downhole use in lost circulation control. In contrast, a one-component system which could be pumped from the top of the well may have some promise because a larger initial volume of chemicals could be emplaced downhole. The isocyanate used in most rigid polyurethane foam systems is a promising starting point for the development of one-component formulations. This chemical, polymeric MDI (polymethylene polyphenyl-isocyanate), will react with itself to form rigid, thermally stable polymers.

One potentially useful technique would be to cap the reactive groups of the polymeric MDI, which would prevent any reaction until exposed to a high-temperature environment. Several schemes have been developed to do this; however, the materials are more expensive than the current two-component system.

Although one or more of these schemes may lead to successful reactive systems that would seal lost circulation zones with polymers made in situ, they would require considerable development before they could be used. Further work on the two-component system does not seem reasonable given the results of the Geysers field test and the Sandia experiments.

CONCLUSIONS

The following major conclusions can be drawn:

1) The polyurethane foam chemical formulations employed in this study are sensistive to jet mixing with water in the downhole environment. At elevated pressures, a significant fraction of the CO_2 gas generated in the chemical reaction is apparently dissolved in the ambient water, thereby reducing the available free gas to expand the foam. As a result,

foam samples generated in the presence of pressurized water are much denser than foam samples generated in an inert environment.

2) Because of the reduced expansion experienced when the foam chemicals are jet-mixed with water, the polyurethane foam formulations and downhole tool as they now exist would be ineffective in plugging lost circulation zones unless the zones are relatively small and can be precisely located. Conditions under which the existing foam system may be effective include: ambient pressures less than 200 psi; wellbore diameters of 10-5/8 inches or less; loss zone intervals less than 10 ft long; loss zones with an overall porosity of 20% or less; and loss zones located less than 10 ft above the bottom of the wellbore.

3) The effects of drilling mud chemistry on the structure of the foam can be significant. The drilling fluid used in the Geysers field test caused premature foaming that may hinder loss-zone emplacement and in the lab tests caused a noticeable reduction in the structural strength of the resulting polymer.

4) The viability of the chemical stock used in the Geysers field test remains a concern. Significant differences in the densities and relative vapor pressures of the chemical components suggest that the chemical stock used in the SwRI tests and the Geysers/Sandia tests were not identical.

NOMENCLATURE

d_W	wellbore diameter (in)
h_L	height of wellbore interval in loss zone (ft)
h_W	height of open wellbore interval below loss zone (ft)
m_c	mass of foam chemicals mixed to make foam sample (lbm)
m_g	mass of free CO_2 gas generated by mass m_c of chemicals (lbm)
P	ambient pressure during foam generation (psi)
R	ideal gas const. for CO_2(35.1 ft-lbm/lbf-^oR)
R_p	radius of ideal foam plug in loss zone (in)
T	absolute temperature of CO_2 gas during foam generation (^oR)
V_c	volume of liquid foam chemicals in the unreacted state (ft^3)
η_L	effective rock formation porosity in loss zone
ρ_c	density of liquid foam chemicals in the unreacted state (lbm/ft^3)
ρ_f	density of foam sample measured at atmospheric pressure (lbm/ft^3)

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