GAS MIGRATION IN CEMENTS: EVALUATION OF ADDITIVES

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ABSTRACT

Gas migration or "gas cut cement" has been an industry problem for many years. This paper discusses the testing of six different cement slurry additives and a saturated saltwater slurry, all designed to prevent gas migration.

The slurries were tested for their effectiveness at preventing gas migration at low pressures, such as is experienced offshore in shallow gas sands. Test equipment of a new design was fabricated. The slurries were exposed to gas pressure at the bottom of a 17 foot cement column in 1-1/2" pipe and the volume of invading gas measured. The hardened columns were then cut into sections to observe the channels created by the gas.

The study showed that none of the products were able to completely stop the gas migration. Some products did appear to perform better than others but none were completely effective. The testing showed several of the slurry's properties to be associated with the formation of gas channels. In many of the tests, unexpected and as of yet unexplained "gaps" developed in the cement columns as the cement hardened. Based on these results, additional testing is being conducted.

INTRODUCTION

From the very early days of cementing many wells had a "little annular gas." This annular gas was usually seen as pressure between the cemented production casing and the previous casing string. The pressure was considered the result of cement channeling or poor bonding of the cement to the formation or pipe. It wasn't until the early 1960's when companies began using old gas reservoirs for liquified petroleum gas (LPG) storage that gas leakage gained serious attention (1). It was at this time the terms "gas migration", "annular gas flow" and "gas leakage" were coined. Today, gas migration is the term generally applied to any gas movement in the annulus of a well that occurs during or shortly after cementing operations.

Many research projects were initiated during the 1960's and 1970's to determine the cause of annular gas. Much of this research was conducted by service companies. The companies found various causes for the gas migration and designed cement systems to combat the problem (2-6). Unfortunately, gas migration was found to be a very complicated process and thus, product design was based on the company's particular view of the problem. As a result, almost all of the service companies gas migration additives function differently.

Texaco has experienced gas migration around the surface pipe in several offshore wells. The severity of this problem has varied from small amounts of pressure in the annulus -- to mud and cement flows at the surface. Several of the service companies have recommended the use of their gas migration additives as solutions to the problem. Some of these additives were used but the success rate was disappointing. Because of these experiences, Texaco's Exploration and Production Technology Division (EPTD) began a program to evaluate the effectiveness of the products at controlling gas migration from shallow low pressure gas zones.

There is no standard industry equipment for the testing of gas migration additives. Each service company has developed their own test devices and performance criteria. The equipment varies significantly from company to company. For this reason, EPTD did not use service company equipment in conducting its tests but built several different laboratory devices designed to objectively test all the products. The final product testing was conducted in a 1-1/2" diameter, 17-foot vertical PVC pipe column (see figure 1). Products from each of the major service companies were tested.

PROCEDURE

Texaco requested that each service company provide a sample of the products they recommend for use in preventing gas migration. They were asked to provide a cement slurry design based on the conditions of the test. Detailed mixing instructions were also requested. Since saltwater cements have been used to combat gas migration, a saturated saltwater slurry was also tested (7).

The testing device consisted of a 17 foot column of 1-1/2" PVC pipe. The use of translucent PVC made it possible to observe any gas movement that occurred. Earlier testing has shown that, under the conditions of this test, the cement slurry behaved the same in both PVC and steel pipe.

Pressure at the bottom of the column was monitored with a sensitive pressure transducer. The hydrostatic head of the cement column supplied the pressure for the testing. No artificial pressuring was used. It was theorized that pressurizing the top of the column would mask cement gel effects. Since gel effects are often cited as contributing to gas migration, artificial pressuring of the column was avoided (8).

The invading gas pressure (nitrogen) was applied at the bottom of the column. The flow rate of the gas was monitored with sensitive mass flow rate meters. The pressure of the invading gas was set at 1 inch of water column below the hydrostatic head of the slurry.

The testing was conducted without fluid loss from the slurry. It is commonly believed that fluid loss is responsible for the loss of pressure at the bottom of a cement column. Earlier testing, conducted by EPTD, had shown that the hydrostatic pressure at the bottom of the column would fall to zero without fluid loss. The effects of gelation/shrinkage alone were enough to cause the loss in pressure (see figure 2). Fluid loss from the column shifted the pressure loss to an earlier time but did not change the slope of the pressure-loss/time curve. Other EPTD testing had shown that fluid loss was controlled by the mud filter cake on the wellbore and not by cement fluid loss additives (9). Additionally, testing without fluid loss would simulate a condition that would be optimal to <u>prevent</u> gas migration and would eliminate the variability of fluid loss. For these reasons the decision was made to conduct the product testing without fluid loss.

The 16.5 ppg slurries were mixed for 20 minutes (3 gallons required for a test) using a large laboratory mud mixer. The normal laboratory cement mixer specified by API, a Waring Blender, shears the cement at a high rate. The mixer used in these tests did not shear the cement at a very high rate and is more representative of the mixing commonly used in field operations.

After mixing, the slurries were pumped into the column from the bottom through a valve. The height of the cement in the column was controlled by pumping until the slurry came out an overflow at the top of the column. Closing the bottom valve then isolated the column.

EXPERIMENTAL RESULTS

General Observations

After the testing was complete the cement columns were sectioned for examination. Although the flow meters indicated the relative amount of gas invasion, the strip charts generated did not correlate very well with the channels observed in the columns. The manner in which the gas moved within the cement column determined how badly the cement column was channeled. In some instances even small amounts of gas were able to cut channels through the cement.

Throughout the testing, gas flow was seen in three different forms:

1) The gas moved into the cement early and bubbled its way through the interior of the cement toward the surface (percolation).

2) The gas moved into the cement early and moved upward as bubbles at the interface of the cement and pipe.

3) As the cement hardened it pulled away from the pipe forming a micro-annulus. Gas would then flow toward the surface through this micro-annulus.

The tests were run until the cement had hardened. After each test, the columns were cut into one foot sections and each section examined for gas channeling and other noticeable characteristics. The photographs shown are sections or "wafers" taken out of the columns to illustrate the appearance of the each.

One of the characteristics noted during the examination was the degree of bonding to the pipe. Although true bonding was probably not occurring, some of the slurries were noticeably tight in the pipe while others were loose; some extremely loose (sloppy). Table 1 indicates how tightly the hardened slurry fit the pipe.

Cement Column Gaps

In the first test, about one hour after the slurry was pumped into the column, a horizontal crack developed in the cement about 2 feet from the bottom. As the test continued this "crack" grew and became a water filled gap in the cement column. After the cement had hardened, the gap was approximately one inch in height and the water had disappeared. Figure 3 shows the gap.

As the testing program continued, similar gaps were seen in many of the columns. Generally the location of the gap was about 2 feet above the bottom of the column.

The development of the gaps in the cement columns was an unexpected result. It's theorized that the gaps may be related to the free water content, shrinkage and gelation properties of the cement. During the hardening process the shrinkage of the cement may cause the cement column to pull apart forming the gaps. Possibly because of the density difference, the free water appears to migrate upward through the cement to collect in the gaps. Whether the gaps are caused by the free water or only act to collect the water is unknown at this time.

A study conducted by Dr. Martin Chenevert at the University of Texas showed that, under certain conditions, cement shrinkage is considerably greater than is commonly believed; on the order of 4% to 5% (10). If these results are true, then cement shrinkage may be at least partially responsible for the gaps. If these gaps do occur in real wells they, may be responsible for many of the "poor cement fill" areas commonly seen on bond logs (11). Texaco is continuing to study this development.

Neat Cement Tests

Column tests were conducted with neat cement to develop a basis with which to compare the additives. The tests were conducted with and without gas pressure applied to the column.

Figures 4 through 6 show the results of neat cement tests. Gas pressure was not applied to the column during one of the tests to produce a control wafer. This control wafer is shown in Figure 4. The cement had no wormhole and was solid. The texture of the cement was normal with no abnormal porosity or graininess. During this test a gap in the cement column appeared approximately 20 inches from the bottom. The gap was small, less than a 1/4" wide.

Figures 5 and 6 are the wafers from tests where gas pressure was applied to the column. In Figure 5 the gas was able to reach all the way to the top of the 17 foot column. The gas movement in the cement was characterized as type 1 above: bubbles which moved through the cement. The gas bubbled its way to the surface of the column,cutting a channel in the process. The cement was solid looking and nonporous. A small 1/8" gap was seen in the column about 24 inches from the bottom.

In the next test, Figure 6, the gas formed a large channel in the lower portion of the column. A large number of gas bubbles were strung up the upper portion of the column. The highest of these bubbles was seen at approximately 10.5 feet from the bottom. Once again, except for the gas channel (wormhole), the cement was solid looking. A 1/4" gap was observed about 40 inches from the bottom.

When examining these columns its was interesting to note that the gas channels were not necessarily continuous from the bottom to the top of the column. The channel would at times disappear in the cement only to reappear further up the column. This was probably due to the cement closing in behind the bubbles as they float toward the surface. The channels became permanent if they were kept open by the gas during the hardening process. It also appears that free water may contribute to this channel making process. If the cement contains excess free water then the bubbles may tend to collect the free water in channels and thus help to maintain an open "cement free" zone. Both of the these neat cement tests contained numerous individual gas bubbles.

In all the column tests, (neat cement and slurries with additives) some gas was flowing to the surface of the column at the end of the test. In all the product tests the gas flow was up a micro-annulus that formed between the cement and the pipe. The amount of gas flow varied from small to large amounts. Those slurries that hardened to a tight fit in the pipe flowed small amounts compared to the slurries where the fit was sloppy.

Product A

The results of the Product A test can be seen in Figure 7. An examination of the column showed the cement to contain many horizontal laminations and small separations. As can be seen in Figure 7, the cement contained a large wormhole in the lower portion of the column that became smaller as it moved upward. The wormhole extended about 73" above the bottom of the column. Although it was not porous, the cement itself was very porous looking.

Product B

Figure 8 shows the results of the Product B tests. Unlike Product A, the column was not porous looking and had only a few laminations. A gas channel (wormhole) extended up through the cement column for the first 12 inches. The gas then moved to the outside of the column at the pipe/cement interface and continued up to approximately 84 inches above the bottom.

During the examination of the hardened cement column it was observed that the cement was very loose in the pipe. This was unlike earlier tests where the cement was tightly locked in the pipe. On many of the 12 inch sections of the column it was relatively easy to push the cement out of the pipe. This loose fit probably indicates that considerable cement shrinkage occurred during hardening. A large amount of gas was flowing at the end of the Product B test. The gas was flowing through this annular space.

Product C

The results of the Product C testing are shown in Figure 9. The sectioned cement column showed the hardened cement to be solid looking; very much like neat cement. The cement was also very tightly stuck to the pipe walls. A wormhole extended up the cement column for about 15 inches and a crack above that to about 50 inches. Above these, near the top of the cement column, there was evidence that the gas had cut a channel at the pipe/cement interface. As in the neat cement tests, a gap developed in the column about 30" from the bottom.

As is evident in Figure 9 the Product C test column also contained a crack. The same type of crack was sometimes seen in the other cement tests. This crack is believed to be caused by gas movement. The cracks were almost always found to start just above a gas cut wormhole. It is theorized that the crack is the result of gas movement that occurs after the cement has begun to gel but before it hardens. As the gas bubbles rise through the cement, at some point the gel strength of the cement will become high enough to stop their movement. If these gas bubbles are in communication with the gas source, (via a wormhole) then the pressure in the bubbles will continue to rise toward the source pressure. If this pressure rise occurs rapidly enough it might finally exceed the fracture strength of the thickly gelled, hardening cement. The pressure required to fracture the cement will be very low during this early stage of the process when the cement is somewhere between a liquid and a solid. The fracture, thus started, will continue to grow toward the top of the column, the rate of growth determined by how well the fracture is communicating will the gas source. With time, the crack growth will stop as the rapidly growing strength of the cement becomes too high for the pressures available. The cement will then complete the hardening with the crack becoming part of the structure.

Product D

The results of the Product D testing are illustrated in Figure 10. On examining the column, the gas movement appeared as the earlier described cracks. A crack was seen in the first 6 inches of the column and small individual bubbles were then strung up the column up to about 10 feet above the bottom. There was no evidence of gas bubbles between the cement and the pipe. The cement matrix was solid looking, with no porous or grainy nature. The cement was slightly loose in the pipe (micro-annulus) but could not be removed from the pipe.

Product E

Figure 11 displays the results of the Product E testing. As can be seen, the gas in the Product E test displayed the crack type of movement. This crack was evident in the lower part of the column and ended at a gap in the cement located 16" from the bottom. The gap was about 1/4" wide. The cement was granular looking and well bonded in the dissected pipe sections.

Product E was an expansive additive. Early during the Product E testing, micro-annular gas flow began as it did in all the other tests. Later in the test, the annular gas flow slowed as the cement hardened. This was one of the few products where this type of behavior was noted.

Product F

The results of the testing are shown in Figure 12. Product F severely retarded the cement. The cement did not begin to set until approximately 18 hours after it had been pumped into the column. When it did begin to set, large bubbles of gas were introduced into the column. These bubbles traveled up the column between the pipe and the cement. This additive caused the cement slurry to become very viscous.

The sectioned cement column contained several large bubbles and channel ways. A small wormhole was found in the bottom 20 inches of the column. The gas then moved to the slurry/pipe interface to continue its upward journey for another 20". There was no visible gap in the cement. The hardened cement was very grainy in appearance and very loose in the pipe.

Saturated Saltwater

Figure 13 shows the results of the test. The saturated salt cement was severely retarded. Although it gelled rapidly, true hardening did not begin until approximately 12 hours after mixing. As the cement hardened, the sparkling salt crystals became a noticeable part of the cement.

When the column was cut and examined a wormhole was found in the first 50". There was no visible gap in the cement and it was tightly bonded in the pipe. The presence of the salt crystals gave the cement a scaly look. Much of the column also had a two-tone color about it.

DISCUSSION

A summary of the test results is shown in Table 1. No product was able to completely prevent the gas migration. All the columns took gas, but the form of gas movement was not always the same. Some relationships were seen during the testing.

The products which caused the largest increase in the slurry viscosity usually had the form of gas movement described as movement between the pipe and slurry interface. Products B and F had this form of movement. It appears that the high viscosity of these slurries help prevent percolation. The high viscosity directed the gas flow to the interface between the slurry and the pipe.

The slurries with the highest viscosity also appeared to shrink the greatest amount during the hardening process. The hardened cement of Product B and Product F were both very loose in the pipe. The annular space which formed as the cement hardened was a very good conductor of gas. The combination of a thick slurry and the shrinkage of the cement (causing it to pull away from the pipe) may have been responsible for the type of gas movement seen with these two products.

All the cement slurries showed signs of micro-annular gas movement. The movement could be very closely correlated with the setting process of the cement. As the cement began the hardening process a micro-annulus would form between the pipe and the cement. The gas would then slowly begin to flow toward the top of the column through this micro-annulus. In most cases the flow would continue to increase as the cement completed its hardening. The exceptions to this were the expanding cements. In the expanding slurries, after reaching a peak about 5 hours into the test, the gas flow rate fell as the cement continued to harden.

Most of the slurries used in testing did contain some free water. In running some of the neat cement tests the 17 foot column was sometimes deviated 2 to 3 degrees from the vertical position. In these tests it appeared that the free water quickly moved to the upper side of the column. The water then rapidly formed a channel through which gas quickly cut its way to the top of the column. This happened much quicker in columns deviated only a few degrees than it did in the truly vertical columns. The presence of free water in the slurry aggravated the gas migration problem.

CONCLUSIONS

1) Under the conditions of the test (low pressure/low temperature - i.e. shallow gas sands) none of the products tested were able to completely prevent gas migration.

2) Cement gelation and hydration were sufficient to cause the columns to lose their hydrostatic pressure. Fluid loss was not necessary for the pressure loss, but it did accelerate the process.

3) Gas movement in the cement slurries was by percolation. Increased slurry viscosity inhibited gas movement while free water aggravated gas movement.

4) Gaps developed in many of the cement columns during hardening. These gaps may be responsible for the poor cement bond areas sometimes seen in bond logs.

5) All the cement slurries tested developed micro-annulus gas movement as the slurries hardened. The expanding additives greatly reduced the amount of micro-annulus flow.

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Table 1
Product Testing Summary

Product Code	Gas Movement	Fit In Pipe	Remarks
Neat Cement 1	204"	Snug	Gas was able to reach the the surface.
Neat Cement 2	126"	Snug	Bubbles strung above the 126" point.
Product A	73"	Snug	Many horizontal laminations.
Product B	12"/84"	Sloppy	12" of wormhole then to 84" at pipe/cement interface.
Product C	50"	Tight	15" of wormhole then 35" of crack type movement.
Product D	6"	Loose	6" of crack type movement small bubbles up to 120".
Product E	16"	Tight	16" of crack type of movement.
Product F	20"/40"	Sloppy	20" of wormhole then to 40" at pipe/cement interface. Severely retarded cement.
Saturated Saltwater	50"	Tight	Cement excessively retarded.

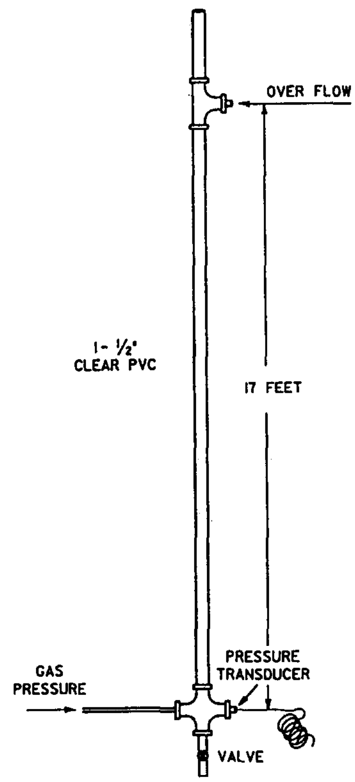

Figure 1 — The 17-foot column

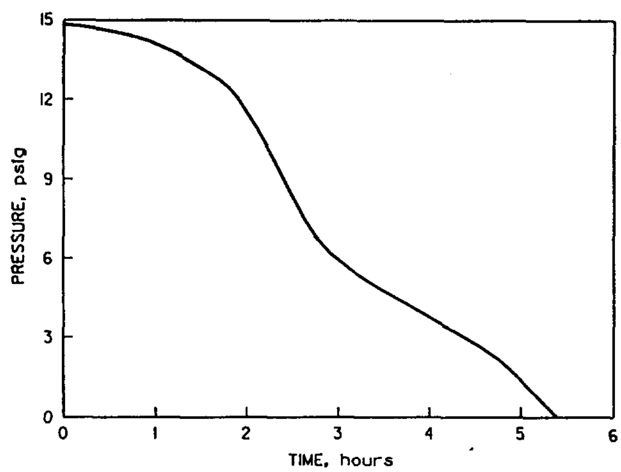

Figure 2 — Loss of hydrostatic pressure in PVC pipe due to gelation and hydration

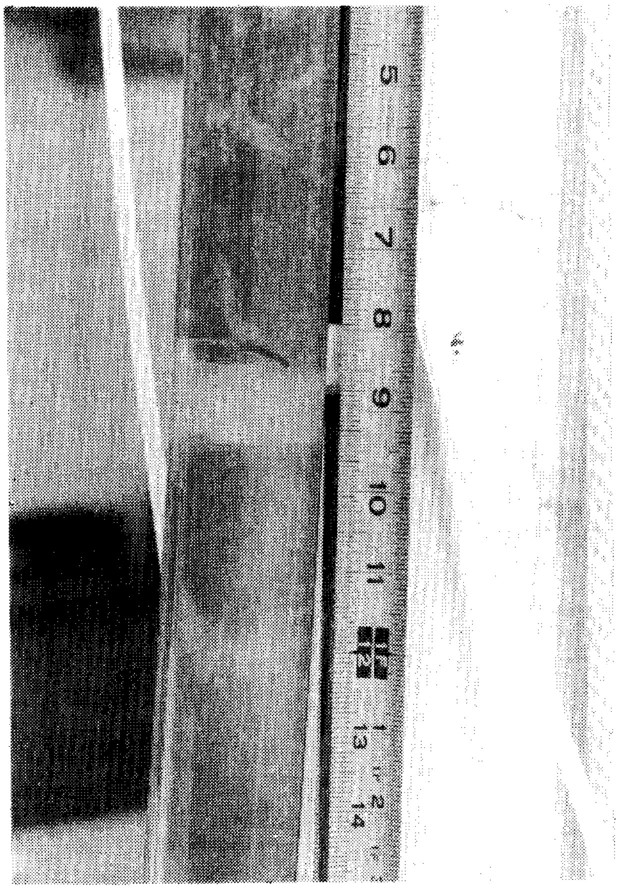

Figure 3 — The "gap" in the 17-foot column

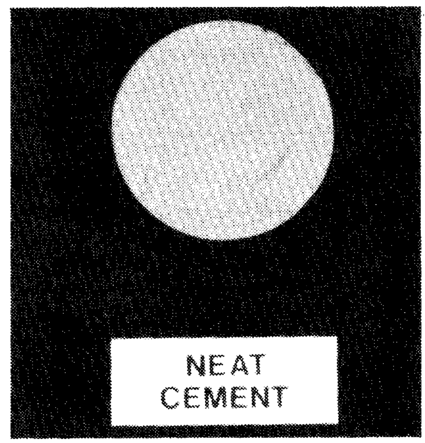

Figure 4 — Neat cement wafer with no gas injection

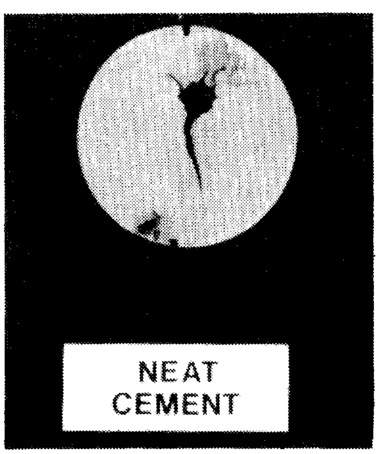

Figure 5 — Neat cement wafer with wormhole and fracture

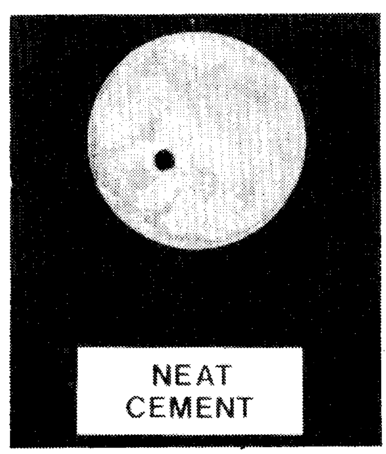

Figure 6 — Neat cement wafer with wormhole

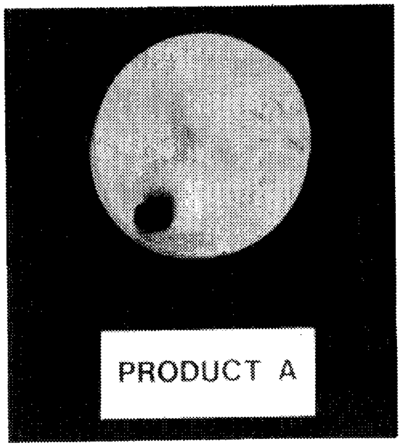

Figure 7 — Product A — wafer with wormhole

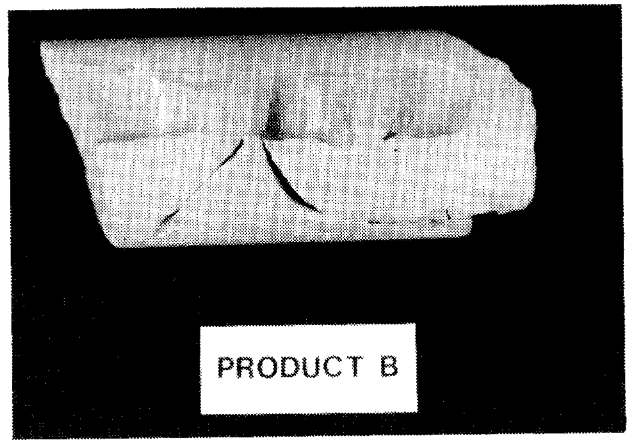

Figure 8 — Product B — wafer with bubbles

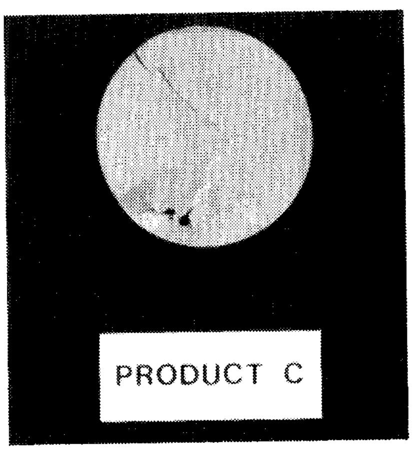

Figure 9 — Product C — wafer with wormhole and fracture

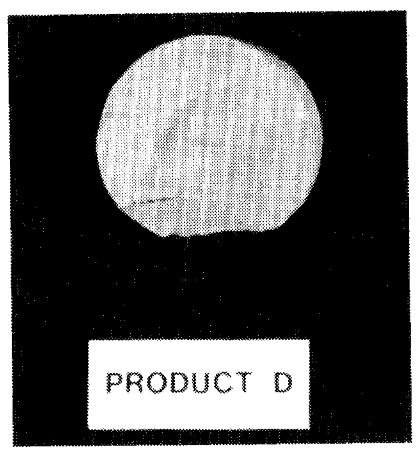

Figure 10 — Product D — wafer with fracture

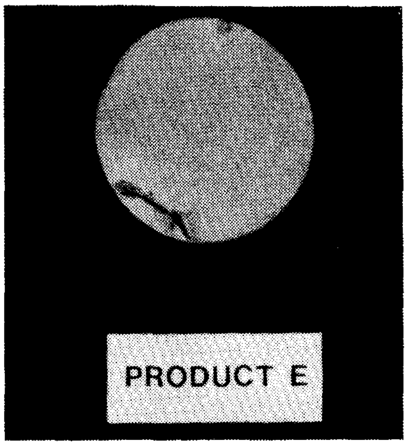

Figure 11 — Product E — wafer with fracture

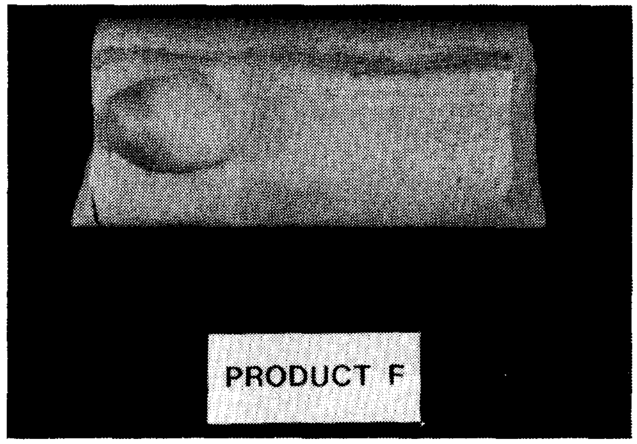

Figure 12 — Product F — wafer with bubbles

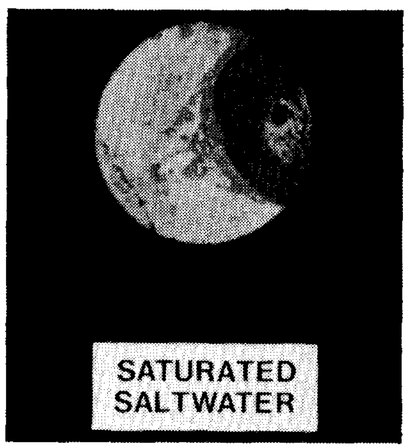

Figure 13 — Saturated saltwater wafer with wormhole