CURRENT STATUS OF GEOTHERMAL WELL CEMENT DEVELOPMENT

L. E. Kukacka
Brookhaven National Laboratory

United States

ABSTRACT

The results of a study made in 1976 indicated that the cements used for well completion deteriorate in the geothermal environments and that the life expectancy of a well, and therefore the economics of geothermal processes, could be improved significantly if better materials were developed. On the basis of this assessment, Brookhaven National Laboratory (BNL) helped the Department of Energy, Division of Geothermal Energy to organize a program to develop materials that meet the estimated design criteria for geothermal well cements. The BNL work involves research on polymer cements and full management of an integrated program involving contract research and industrial participation. The program consists of the following phases: (1) problem definition, (2) cement research and development, (3) property verification, (4) downhole testing, and (5) cementing of demonstration wells.

Phases 1 and 2 have been completed. Characterization of cements selected from the R&D phase or supplied by industry and foreign users (Italy, New Zealand, and Japan) is in progress in Phase 3. All of the materials being evaluated have met API mixing and pumpability standards. To date, based upon the results from compressive and tensile strength measurements after exposure to brine at 300°C (572°F), 12 materials have met the design criteria for those properties. Bond strength to steel casing and permeability measurements are in progress. The evaluation of these 12 well cements will be continued in the downhole test phase of the program.

Plans for initiating downhole testing at Cerro Prieto of precured, in situ-cured, and pumped slurries have been formulated. The latter will represent the first known test of retrievable cements pumped into and cured in actual downhole environments. Tests in flowing brine at two temperatures, ~210° and 350°C (~410° and 662°F), are planned.

This work is scheduled to start in the fall of 1980. Contingent upon the results, cementing of demonstration wells will take place in fiscal year 1982.

In this paper, results obtained in Phases 1, 2, and 3 of the work are summarized and the current status of the downhole testing phase presented.

DISCLAIMER

INTRODUCTION

Geothermal wells are completed in much the same manner as conventional oil wells; however, the environment with which completion materials must contend in a geothermal well can be much more severe. For example, the bottom hole temperature in a geothermal well can be as high as 370°C, and the formation brines downhole are often extremely saline and corrosive. Failure of a geothermal well due to inadequate cementing materials could result in severe economic and environmental consequences.

The results of a survey made in 1976 by Brookhaven National Laboratory (BNL) indicated that the cements used for well completions deteriorate in geothermal environments, and that the life expectancy of a well and therefore the economics of geothermal processes, could be improved significantly if better materials were developed. On the basis of this assessment, BNL helped the U.S. Department of Energy/Division of Geothermal Energy (DOE/DGE) to organize a program to develop materials that meet the estimated design criteria for geothermal well cements. These are as follows:

1. Compressive strength, >6.9 MPa (1000 psi) 24 hr after placement.
2. Permeability to water, <0.1 millidarcy.
3. Bond strength to steel casing, >69 kPa (10 psi).
4. Stability, no significant reduction in strength or increase in permeability after prolonged exposure at 400°C to 25% brine solutions, flashing brine, or dry steam.
5. Placement ability, capable of 3- to 4-hr retardation at expected placement temperatures.
6. Compatibility of the cement with drilling mud.
7. Noncorrosive to steel well casing.

The program consists of the following phases: 1) problem definition, 2) cement research and development, 3) property verification, 4) downhole testing, and 5) cementing of demonstration wells. Programatic responsibilities assigned to BNL included research on polymer cements and full management of the program which involved contract research and industrial participation.

As a means of obtaining technical guidance for the overall program and to assist in the technology transfer process and in the establishment of standards, BNL organized a "Geothermal Well Cement Advisory Panel" which was subsequently affiliated with the American Petroleum Institute (API) as a Task Group of Committee 10, "Standardization of Oil Well Cements". The API Committee Chairman is Mr. H.J. Beach of the Gulf Research and Development Company. Mr. J.P. Gallus of Union Oil of California is Chairman of the Task Group. Representatives from cement manufacturers, research organizations, well completion companies and geothermal well owners serve on the task group.

The program was initiated in July 1976. To date, Phase 1 and 2 have been completed. Characterization of cements selected from the R and D phase or supplied by industry and foreign users is in progress in Phase 3. All of the materials being evaluated have met API mixing and pumpability standards. Plans for downhole testing at Cerro Prieto of cements selected on the basis of the results from Phase 3 have been made and the work initiated. Contingent upon the results from the downhole tests, the cementing of demonstration wells is planned.

In this paper, results obtained in Phases 1-3 of the work will be summarized and the current status (November 1980) of the downhole testing phase presented.

RESULTS

Phase 1. Problem Definition

During the period May - September 1977, the Dowell Division of Dow Chemical, U.S.A., as part of a R and D contract with DOE/DGE, gathered background information on high temperature cementing and related problems. Many publications on high temperature cementing were studied and Dowell proprietary research findings and cementing records were reviewed.

A major source of information for this study was a series of interviews with engineers and drilling personnel of companies having geothermal drilling and completion experience. This enabled definition of current cementing practices and problems and helped set objectives for research.

Information concerning the following items was compiled.

1. The expected well life of geothermal wells in different type fields.
2. The expected characteristics for geothermal brines and steams.
3. The static and circulating temperatures expected for the various types of fields.
4. The weight range required for geothermal cement slurries.
5. Typical casing programs for geothermal wells.
6. The minimum acceptable performance criteria for geothermal cements.
7. The bonding ability of cements to geothermal formations and casing.
8. The thermal variations expected during the life of a well.
9. The type of drilling muds expected to be used in geothermal wells.
10. Economic limitations on geothermal completion systems.

The results from this survey have been published in an interim report [1] and will be incorporated into Dowell's final report on geothermal well completion systems [2]. The principal findings were that the circulating temperature of fluids during completion is substantially lower than the static temperature. Maximum fluid circulating temperatures, where measured, seldom exceed 116°C. As a result, cements must be able to withstand severe thermal shock when the well is brought into production.

All operators expressed concern over the cement to pipe bond, when subjected to temperature cycling as a result of drilling, testing, shutting in, and producing. In feasible areas, wells are left on a bleed system to maintain temperature, but in most areas this is not possible. Several operators expressed concern over the possible changes in permeability from microfractures in the cement sheath induced by thermal shock.

Another important consideration is the inherent fragility and fluid nature of geothermal formations. Almost every operator expressed a need for lightweight cement slurries, in the range of 1.44 kg/l (12.0 lb/gal) or less, to prevent the occurrence of formation damage and lost circulation.

Well completion costs are in general ~4% of the total well cost and ~50% of this amount represents the cost of the cement [3]. Information obtained by Dowell indicated that the cement cost for typical wells varied from $17,000 to $50,000. One operator indicated that a 10% increase in the cement cost could be accepted if performance improvements were demonstrated.

Phase 2. Research and Development Programs

A series of R and D programs to develop cements specifically for geothermal applications was started. In addition to BNL, organizations participating in this phase of the program were Battelle's Columbus Laboratories (BCL), Colorado School of Mines (CSM), Dowell Division of Dow Chemical U.S.A., Pennsylvania State University (PSU), Southwest Research Institute (SwRI), and the University of Rhode Island (URI). All of these projects have been completed and final reports published [2,4-9].

The R and D effort consisted of the characterization of cements currently used in geothermal environments [2,4], the extension of hydrothermal cements to higher operating temperatures [7], and the development of new materials such as phosphate-bonded cements [8], polymer cements [9], and new compositions within $CaO-MgO-SiO_2-H_2O$ and $CaO-Al_2O_3-SiO_2-H_2O$ systems [6].

All the above programs with the exception of the one at URI have produced one or more cementing materials which in general meet the property criteria given previously. They also meet the API mixing and pumpability standards. These cement formulations, summarized in Table 1, are currently being subjected to additional evaluation at the National Bureau of Standards.

In addition to the cements identified in this phase of the program, several cements currently being used in the U.S.A. and foreign countries were submitted for evaluation. Sources of these materials, data for which are also given in Table 1, were the Italian National Energy Agency (INEL), New Zealand Department of Scientific and Industrial Research (DSIR), Ube Industries, Ltd. (Japan), and Halliburton Services.

Phase 3. Property Verification

The National Bureau of Standards (NBS) is currently performing tests on cements identified in the R and D phase of the program and on materials submitted by private industry and foreign geothermal developers. Prior to submission, documentation was provided by the suppliers that the cements met the previously discussed property criteria and that they passed the API thickening time requirement for a Class J cement in a 3050 m well depth. This requirement specifies that the slurry must have a consistency <30 Bc during the initial 30 min of the stirring period and a consistency <100 Bc up to 3 hr of the stirring period.

Prior to commencing tests at NBS, procedures for measuring compressive strength, tensile splitting strength, shear-bond at the cement-steel interface and cement permeability to water, were compiled by NBS and approved by the API Task Group on Geothermal Cements [10,11]. In addition, a high temperature high pressure fluid handling facility was constructed. The facility allows set cements to be exposed to simulated geothermal fluids at pressures up to 60 MPa

(8,700 psi) and at temperatures up to 400°C. Two of the pressure vessels are equipped for measuring either the shear-bond strength or the permeability at elevated temperatures and pressures. Descriptions of these components are given in Ref. 12.

The cement slurries are prepared in accordance with API recommended practice [13]. Specimens are then set-cured in molds under water for 2 days at elevated temperature and pressure. Subsequently, the specimens are exposed demolded to light and heavy simulated geothermal fluids for periods of 1 week or 1 month. Following each of these treatments, the properties mentioned above are being measured at room temperature and pressure. Upon the basis of this survey of properties at room temperature, a priority of cementing materials will be established for further testing of select physical properties while the specimens are at elevated temperature and pressure.

To date, partial test results are available for 16 cements and based upon these results, 9 were selected for additional study. Data for these 9 materials are summarized in Tables 2-5. Cements identified O-V,X, Y and α in Table 1 have not yet been placed in test.

Compressive strength data (Table 2) obtained after curing the slurries at 200°C and 20 MPa (2,900 psi) for 2 days indicate strengths exceeding the specified minimum of 6.9 MPa (1,000 psi). Values ranged from 25.1 MPa (3,640 psi) for a lightweight [1.55 kg/l (12.9 lb/gal)] Japanese cement to 71.4 MPa (10,350 psi) for a Halliburton Services - supplied Class G cement stabilized with 80% silica flour. Measurements made after 7 and 28 day exposures to water at 200°C and 20 MPa (2,900 psi) pressure were in general agreement with the 2 day strengths. No significant strength regression with time was observed.

Data after 7 and 28 day exposures to 20% brine at 300°C and 20 MPa (2,900 psi) are available for 6 cements. No appreciable deterioration with time is apparent and 4 formulations (B,D,L and Z), had strengths similar to those after the 200°C exposure.

Tensile splitting strength data are given in Table 3. As expected, trends similar to those exhibited by the compressive strength specimens were obtained.

Shear bond strengths at the interface with sandblasted steel surfaces are given in Table 4. Compared to the bond strength criteria of 69 kPa (10 psi), all of the cements greatly exceeded that value. Little change in bond with exposure time was evident, but the values at 300°C were lower than those at 200°C.

Data summarizing the permeability to water after exposure to water at 200°C and brine at 300°C are given in Table 5. A value of 0.1 millidarcy (md) is considered adequate for a well completion material. As noted in Table 5, the data exhibit considerable scatter. Values ranging between 0.03 and 110 microdarcy (μd) were measured. Trends toward increased permeability with increasing exposure time and temperature are evident, but based upon work published by Gallus, Pyle and Watters [14], it would be expected that the long-term permeabilities would stabilize at values below 1 md.

Testing of each of the above cements will be continued at NBS. Permeability and bond strength measurements will be made at high temperature. In addition, they will be evaluated in the downhole testing phase of the program which is described below. Similar tests will be performed on formulations O-V,X,Y and α, and from these materials additional cements will be chosen for downhole evaluation.

Phase 4. Downhole Testing

An agreement to test candidate well cementing materials in Mexican wells at Cerro Prieto as a cooperative effort between the Instituto de Investigaciones Electricas (IIE), Comision Federal de Electricidad (CFE), and BNL has been established and work is in progress. The API Task Group on Geothermal Cements will act in an advisory capacity and provide technical assistance.

The initial tests are being performed in Cerro Prieto Well Q-757. Initially, 2 types of test specimens, pre-cured and in-situ cured, will be exposed downhole to flowing brine at the following conditions: temperature 210°C, pressure 9.2 MPa (1,330 psi), pH 6.8, chloride content 6,395 ppm and SiO_2 content 347 ppm. The well depth is 935 m. Both series of tests will be performed using the techniques described in Ref. 14. Contingent upon the results, pumpdown tests will be performed in this well and the entire series of tests repeated in a higher temperature (~340°C) well.

The pre-cured series will consist of 5-cm cubes cured in an autoclave at the downhole pressure and temperature. A maximum of 20 cements will be tested. Sources tentatively will be as follows: 15 DOE/DGE, 3 currently used U.S.A. cements, and 2 cements used at Cerro Prieto.

Four cubes of each cement in this test series will be removed after each of the following exposure times: 3 mo, 6 mo, and 12 mo.

The in-situ cured series will be prepared by filling hollow Berea sandstone cores with the cement slurry and then lowering the containers into the well where the cements will cure in the downhole environment. The limestone cores will be ~10-cm. long x 10-cm-diam with a 7.6-cm- hole drilled axially to a depth of 7.6-cm into the cylinders.

Two in-situ cured specimens of each cement will be removed after exposure for 1 day, 3 mo, 6 mo and 12 mo.

Half of the specimens will be tested at NBS and the remainder by IIE. Tests to be performed include compressive strength, permeability, scanning electron microscopy (SEM) and x-ray diffraction.

Placement of the first samples in the well is scheduled for January 1981. To date, de-scaling of the well casing to insure easy access for the sample holders has been performed, the pressure-temperature profile in the well determined, and preliminary specimens cast for use in tests to determine the degree of reproducibility that can be expected between NBS and IIE.

Upon successful start-up of the downhole tests, work will commence on an above-ground chamber for use in well-head evaluations. Plans for pumpdown and high temperature (~340°c) tests will commence when data from the first series of tests become available (~6 mo).

SUMMARY AND CONCLUSIONS

This paper summarizes the status of a DOE/DGE funded program to develop cement systems suitable for the completion of geothermal wells. Management of the program is being performed by BNL with technical review provided by the API Task Group on Geothermal Cements.

The program represents the most comprehensive and thorough examination of the geothermal cementing problem undertaken thus far. It consists of 5 phases: 1) problem definition, 2) cement research and development, 3) property verification, 4) downhole testing, and 5) cementing of demonstration wells. To date, Phases 1 and 2 have been completed and work is in progress in Phases 3 and 4.

The characterization of 26 cements identified in the R and D phase or supplied by industry and foreign users is in progress at NBS. Several cements with excellent properties have been identified. Perhaps the most significant observation to date is that portland cements of normal weight, similar to those already in use at most geothermal areas, have shown little deterioration after exposure to 20% brine at 300°C and 20 MPa (2,900 psi) pressure for 28 days. This should be reassuring to operators who are currently using such slurries. Also, based upon the screening and chemical studies efforts, some promising lightweight systems based upon special modifications of portland cement have been identified. These will be important in reducing formation damage and lost circulation problems.

A downhole testing program has been established at Cerro Prieto and work is in progress. This hopefully will culminate with the first known test of retrievable cements pumped into and cured in actual downhole environments. Tests in flowing brine at 2 temperatures (~210° and 350°C) are planned. The first samples in this test series are scheduled to be placed downhole in January 1981.

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Table 1

Candidate Geothermal Cements Selected From DGE-Sponsored R and D and From Other Sources

Source	ID	Components	Concentration, parts by weight
Dowell	A	API Class G cement	100
		silica flour	35
		water	54
		lignin-sugar retarder	1
Dowell	B	API Class J cement	100
		water	44
		lignin-sugar retarder	0.4
BNL	C	solid aggregate	100
		liquid organic monomers	22
INEL	D	cement	100
		water	45
		retarder	0.7
CSM	E	modified B-C_2S cement	100
		perlite	4.5
		bentonite	1.1
		water	85
DSIR	F	API Class G cement	30
		pozzolan	40
		blast furnace slag	30
		water	60
		carboxy methyl cellulose	0.5
DSIR	G	API Class J cement	30
		silica flour	40
		pozzolan	30
		water	60
		carboxy methyl cellulose	0.5
SwRI	H	hydrothermal cement	100
		water	20.8
Ube	I	cement	100
		water	50
		retarder	0.3

Table 1 (cont'd)

Source	ID	Components	Concentration, parts by weight
DSIR	J	portland cement	100
		water	50
Dowell	K	API Class G cement	100
		silica flour	35
		bentonite	2
		perlite	8.5
		water	116
Dowell	L	API Class G cement	100
		silica flour	35
		diatomaceous earth	10
		water	91
PSU	M	API Class J cement	80
		calcined chrysotile (M_3S_2)	20
		water	47.5
		D-28 Dowell retarder	0.25
PSU	N	system CA-CA_2 cement	100
		5 μm quartz	100
		water	89.1
		100 XR Pizzolithe	0.9
PSU	O	API Class J cement	60
		calcined chrysotile (M_3S_2)	40
		water	47.5
		retarder	0.[illegible]75
BNL	P	solid aggregate	100
		liquid siloxane monomer	50
Dowell	R	API Class B cement	100
		silica flour	35
		NaCl	20
		water	54
		lingnin-sugar retarder	1
Dowell	S	API Class G cement	100
		silica flour	100
		sodium silicate	2
		NaOH	1
		water	135
		lignin-sugar retarder	1

Table 1 (cont'd)

Source	ID	Components	Concentration, parts by weight
BCL	T	API Class J cement	30
		silica flour	30
		blast furnace slag	40
		water	50
		carboxy methyl cellulose	0.5
BCL	U	API Class J cement	30
		pozzolan	30
		blast furnace slag	40
		water	50
		carboxy methyl cellulose	0.5
Ube	W	lightweight cement	100
		water	68
		retarder	0.2
Halliburton	X	API Class G cement	100
		silica flour	40
		water	60
		dispersant	0.75
		retarder	0.4
		fluid loss additive	0.75
Halliburton	Y	API Class G cement	100
		silica flour	100
		water	44
		retarder	0.3
Halliburton	Z	API Class G cement	100
		silica flour	80
		water	77
		retarder	0.3
		fluid loss additive	0.5
Dowell	α	API Class A cement	100
		silica flour	25
		glass spheres	40
		water	115
		retarder	0.6

Table 2

Compressive Strength After Exposure to Various Fluids, All At 20 MPa Pressure

Cement ID	Set-cure, 200°C for 2 day	Exposure to water at 200°C for 7 day	Exposure to water at 200°C for 28 day	Exposure to 20% salt water at 300°C for 7 day	Exposure to 20% salt water at 300°C for 28 day
	Compressive strength, MPa				
A	64.0±9.3	40.4±9.6	28.6±5.2	14.8±1.1	16.8±1.0
B	51.8±7.1	20.5±2.6	23.7±1.6	28.6±3.0	32.1±1.9
D	52.2±2.4	48.6±4.5	46.7±5.5	33.1±8.4	45.9±14.2
I	39.2±1.5	37.2±6.4	51.7±1.0	——	——
L	27.2±1.2	27.9±3.0	25.7±2.8	35.2±8.6	52.5±0.8
M	40.3±4.8	——	——	25.8±1.0	——
P	59.7±4.2	68.7±1.4	74.3±4.2	83.9±10.2	——
W	25.1±0.6	24.2±1.9	23.4±1.1	20.5±1.5	17.9±2.2
Z	71.4±2.1	34.2±0.3	30.5±3.6	39.9±1.0	33.8±1.8

Each value represents average of 3 test specimens.
1 MPa = 145 psi

Table 3

Tensile Splitting Strength After Exposure to Various Fluids, All At 20 MPa Pressure

	Tensile splitting strength, MPa				
	Set-cure, 200°C for	Exposure to water at 200°C for		Exposure to 20% salt water at 300°C for	
Cement ID	2 day	7 day	28 day	7 day	28 day
A	7.40±0.90	7.43±0.70	4.64±0.53	2.20±0.31	1.96±0.19
B	5.99±0.43	3.06±0.23	3.48±0.49	4.88±0.59	5.12±0.46
D	5.84±1.83	5.31±1.50	3.68±0.27	3.54±0.81	6.61±1.84
I	4.09±0.65	4.19±0.66	5.66±0.70	——	——
L	3.65±0.91	4.24±0.34	4.05±0.54	6.53±0.67	6.56±0.39
M	3.90±0.27	——	——	3.93±0.24	——
P	3.71±0.99	5.01±1.13	6.64±0.82	9.22±1.54	——
W	2.36±0.49	2.98±0.18	2.85±0.15	2.79±0.41	2.69±0.18
Z	7.68±0.87	5.37±0.44	5.32±0.36	6.12±0.49	5.67±0.13

Each value represents average of 3 test specimens.
1 MPa = 145 psi

Table 4

Shear-Bond Strength at Sandblasted Steel Interface After Exposure to Various Fluids, All At 20 MPa Pressure

Cement ID	Shear-bond strength, MPa: Exposure to water at 200°C for 7 day	Exposure to water at 200°C for 28 day	Exposure to 20% salt water at 300°C for 7 day	Exposure to 20% salt water at 300°C for 28 day
A	19.7	12.4	6.4	9.7
B	18.2	19.3	13.8	21.6
D	24.9	24.3	——	18.0
I	17.1	20.0	10.1	21.0
L	15.8	15.0	10.3	8.2
M	15.4	15.3	8.9	4.3
P	1.6	1.8	0.3	0.3
W	13.9	12.7	6.7	6.6
Z	13.8	12.2	5.9	9.1

1 MPa = 145 psi

Table 5

Permeability to Water at 25°C After Exposure to Various, Fluids, All At 20 MPa Pressure

Cement ID	Permeability, microdarcy Exposure to water at 200°C for 7 day	 28 day	 Exposure to 20% salt water at 300°C for 7 day	 28 day
A	0.71	5.3	0.033	29
B	4.9	11	9.1	10
D	4.8	12	9.4	21
I	11	15	40	69
L	48	110	48	51
M	2.1	1.2	1.9	2.1
P	13	——	——	15
W	14	16	43	88
Z	2.5	2.0	5.4	4.0

1 MPa = 145 psi