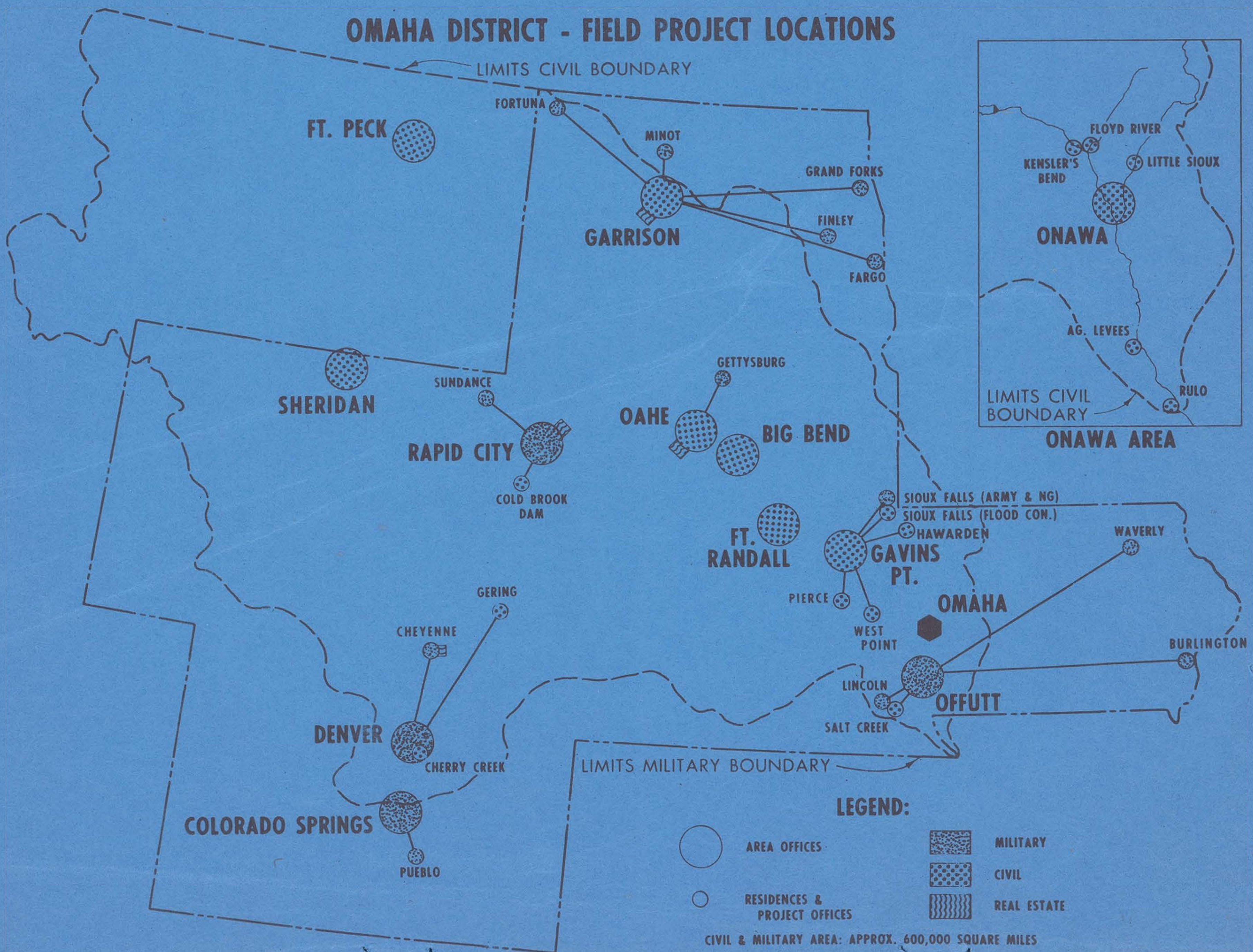
NORAD C.O.C.
COLORADO SPRINGS, COLORADO

REPORT OF INVESTIGATION OF CHEMICAL GROUTS FOR ROCK BONDING

EVALUATION OF THE EFFECTIVENESS OF EPOXY RESIN AND POLYESTER RESIN TO STRENGTHEN FRACTURED GRANITE AT NORAD C.O.C.

U. S. ARMY ENGINEER DISTRICT, OMAHA
CORPS OF ENGINEERS
OMAHA, NEBRASKA
JULY 1963

OMAHA DISTRICT - FIELD PROJECT LOCATIONS



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PREFACE

The investigation described herein was accomplished with funds furnished by the Office, Chief of Engineers to study the feasibility of bonding rock by injection of chemical grout. The report will be in two parts as discussed in the Summary.

The tests were conducted at NORAD under the direction of the Omaha District office with the cooperation of the U. S. Bureau of Mines, the Ohio River Division Laboratories, Missouri River Division Laboratory and the Colorado Springs Area office. The tests and preparation of the report were made under the general direction of Mr. Lyman S. Bray. The field tests were under the direct supervision of Mr. Herbert B. Erickson, who also prepared this report.

Excellent cooperation and helpful suggestions were furnished by the (P-1) Company and the (E-1) Company technical representatives.

Specific mention is made on the assistance provided by Mr. B. U. Duvall of the Ohio River Division Laboratories and Mr. R. H. Oitto of the Bureau of Mines.

Colonel Harry G. Woodbury was the Omaha District Engineer, Mr. Charles L. Hipp was the Chief of the Engineering Division, and Mr. H. A. Sikso was the Chief of the Foundations and Materials Branch during performance of the test work and the preparation and publication of this report.

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REPORT OF LABORATORY PILOT STUDIES FOR ROCK BONDING WITH CHEMICAL GROUTS - OHIO RIVER DIVISION LABORATORIES - TECHNICAL REPORT NO. 2-31, JUNE 1963

APPENDIX B

LOG OF INJECTION

APPENDIX C

STRATASCOPE LOG

KEY

Manufacturer	Symbol	Material
George W. Whitesides Company 3048 Michigan Drive Louisville, Kentucky	(E-1)	62 E 2
American Cyanamid Company Stamford Research Laboratories 1937 West Main Street Stamford, Connecticut	(P-1)	Resin-Laminac 4151 Catalyst-Lupersol DDA-15 Promoter-Dimethylaniline (DMA) Dye-Calcofluor HEB yellow

SUMMARY

The Northeast corner of the A-2 Intersection (Corner No. 3) at NORAD (See Figure 1) has been a problem to stabilize since the area was first excavated. Geologic defects were noted during the initial development and some movement occurred along major joints prior to June 1962. The opinion of consultants on proper treatments to improve rock stability was divided. Eventually a compromise design was developed which was based on partial removal of the rock and bolting or "pinning" of the remaining loose rock. This plan was adopted and during January 1963 while excavation was proceeding, excessive movements were noted on rebound gages, and it was clearly evident that the static stability of the intersection was being effected by the blasting and rock removal efforts. Further rock removal was suspended pending further evaluation of the plan.

The investigation described herein was devised to study the effects of two chemical grouts on bonding the rock to produce stability. Laboratory tests were made first, to determine if appreciable bond could be developed to the moist rock, then test injections of epoxy resin (approximately 50 gallons, E-1) and polyester resin (approximately 200 gallons, P-1) were made, and the results of these injections were evaluated by drilling NX cores in the area and studying the cores and observing the core holes with a stratascope.

This investigation is divided into two parts, and it will be covered by two separate reports. This is the first part and it will cover the laboratory testing, test injections, evaluation, and selection of epoxy resin grout for the final grouting to stabilize the rock in the entire corner.

The second part of the report will cover the planned injection of approximately 2500 gallons of epoxy resin on a production basis to stabilize the entire northeast corner of the A-2 Intersection. It will include injection data, evaluation information obtained from core drilling, and movement data.

The results of test grout injection were as follows:

a. The epoxy resin grout was selected in preference to the polyester resin for the final grouting to stabilize the entire northeast corner of the A-2 Intersection for the reasons given below.

(1) Examination of the cores indicated that the epoxy resin had developed much better bond to the moist granite.

(2) The epoxy resin was found by the Ohio River Division Laboratories tests to be less brittle and have less shrinkage. Limited photoelastic studies in the ORD Laboratories showed that the epoxy resin used did not develop the setting stresses that were found in the polyester resin after hardening.

b. The epoxy resin used during the test was more viscous than the polyester resin but the manufacturer indicated he could reduce the viscosity if his material was selected for the final grouting. Stratascope observation of the core holes and visual examination of the cores indicated slightly better penetration for the polyester resin in small cracks, but this was not believed sufficient to balance the other more favorable characteristics of the epoxy resin, especially since the viscosity of the epoxy resin could be reduced.

REPORT OF
INVESTIGATION OF CHEMICAL GROUTS FOR ROCK BONDING

PART I: INTRODUCTION

Background

1. As was indicated in the summary, stabilization of the northeast corner of the A-2 Intersection has constituted an interesting but perplexing problem. Representatives of the Missouri River Division and the Omaha District had heard of the experimental work on rock bonding being done by injection of chemical grout in heavily loaded portions of mines by the U. S. Bureau of Mines, so their Roof Control Research Group was contacted to see if this method might be used to stabilize the A-2 corner.

The Roof Control Research Group of the Health and Safety Research and Testing Center of the U. S. Bureau of Mines in Pittsburgh, Pennsylvania, has conducted research in rock bonding since 1956. They have worked quite closely with the (P-1) Company in this work. The test work was largely done with a polyester resin grout produced by the (P-1) Company, and the injection work has mostly been done as a joint effort of the U. S. Bureau of Mines and the (P-1) Company.

Mr. H. B. Erickson of the Omaha District visited the Homestake Mine at Lead, South Dakota, on 21 July 1962 in company with Mr. R. H. Oitto of the U. S. Bureau of Mines who had done the chemical grout injection work there. The U. S. Bureau of Mines has not made a final report on the results of rock bonding but they informally indicated, as did the Assistant Mine Superintendent, Mr. W. C. Campbell, that the area which had been treated there appeared to be improved structurally and was showing less deterioration than the adjacent areas at each end of the treated area which were all subjected to the same loading. This was also apparent to Mr. Erickson of the Omaha District during his visit.

On 20 August 1962, a visit was made to the A-2 Intersection at NORAD by Mr. R. H. Oitto, Mr. T. J. Reading of the Missouri River Division, Messrs. D. C. McLean and L. McKenna of the (P-1) Company, and Messrs. J. M. Zeltinger and H. B. Erickson of the Omaha District. Lt. Col. J. P. Beeson, Colorado Springs Area Engineer, and Mr. S. R. Smith, Chief of the Engineering and Technical Branch of the Colorado Springs Area Office, attended the conference in the field office that was held to discuss the findings at the end of this visit. It was decided that bonding of the moist granite, which contains faults with poorly bonded coatings of magnetite, chlorite and calcite as well as loose clay in some cases, would be difficult and laboratory tests were recommended.

In order to evaluate the possibilities of bonding with polyester resin, it was decided that samples of the granite with the coatings would be forwarded to the Missouri River Division Laboratory for testing. The rock was to be moistened, bonded with the polyester resin, and then cores would be drilled through the bonded sections and the bond would be tested for compression, tension and shear. This was done and a summary of the results of laboratory tests is given in detail in paragraph 3 which follows and in Appendix A. Basically, the simple tests indicated that bond could be developed in a sufficient amount that a test injection in the rock at the A-2 Intersection to determine how the grout would penetrate and bond the actual rock in place was justified. Funds to make a trial injection of polyester resin grout were requested from the Office of the Chief of Engineers. These funds were made available without delay in order that the injection could be made quickly before construction progress made access to the corner impossible.

Geology of A-2 Corner

2. Following excavation of the chambers, it was noted that significant rock movement had occurred in the NE corner of Chamber A-Chamber No. 2 intersection. Rock movement occurred along well-defined existing joint and shear planes with the maximum movement occurring on the plane of a N30°W shear dipping 30° to 50° SW into the intersection. Since rock below the N30°W shear plane was excavated, the lateral restraint was removed from the hanging wall of the shear plane; this, then, enabled the rock of the hanging wall to move when subjected to the load imposed by stress adjustments around the opening. As a consequence of the major rock movement, in addition to high stress concentrations due to the opening, readjustments of rock in the hanging wall block were evidenced by numerous narrow cracks. These cracks are probably the result of stress relief along weak discontinuities within the rock mass.

Laboratory Tests Before Test Injection

3. A sample of the polyester resin which was to be used in the test injection was obtained and furnished to the Missouri River Division Laboratory. Their report of the testing has been incorporated in this report. In accordance with instructions from Office of the Chief of Engineers, arrangements were made with the Ohio River Division Laboratories to secure and test samples of an epoxy resin which the Ohio River Division Laboratories had proposed to use for test grouting. The Ohio River Division Laboratories also secured a sample of the polyester resin which was intended to be used in the test injection to make comparative tests with the epoxy resin. Sections of cores from exploratory drilling at NORAD were selected and furnished to the Ohio River Division Laboratories for their tests. Their report is attached as Appendix A to this report.

a. <u>First Polyester Resin Test in MRD Laboratory (Lab No. 62/736A-B)</u>.

(1) <u>Test Procedure</u>. Selected chunks of rock were matched for fit along joint surfaces and cemented together with Hydrocal along the edges, except for a small opening at one end. This made a joint opening between the two chunks of rock which varied in width from 1/64 to 1/2 inch, depending on the irregularity of the two rock faces. After the Hydrocal hardened, the blocks were wetted to produce a moist condition of the joint faces to be bonded with polyester resin. None of the joint faces with their chlorite and carbonate deposits were cleaned in any way. The polyester resin was mixed in accordance with the manufacturer's directions and poured into the joint until it overflowed out of the pouring vent. After the polyester resin had hardened for 18 hours, two-inch diameter cores were drilled out of the rock blocks. It was discovered upon drilling that the core would always break in bond at the polyester resin filled joint, so that a complete core through both pieces of rock could not be obtained. One of the cemented blocks was then sawed in half across the resin-filled joint and was observed to have a small shrinkage crack at the interface between the resin and the rock face. Since the cores could not be obtained intact by the method described above, cores were drilled and then cemented together along joint faces, which were placed essentially normal to the length of the core, with the polyester resin. The surfaces were moist, but were not excessively wet, when the resin was applied. The joint thickness varied from almost nothing to about 1/4 inch depending on the condition desired for test. A minimum of 24 hours and in most cases about 72 hours of hardening was allowed before the rock cores were tested for tensile and compressive strengths. A total of five cores were tested in tension and five in compression. The compression and tensile strengths of the polyester resin were also obtained according to ASTM methods D695-61T and D638-61T respectively.

(2) <u>Tensile Strength</u>. One of the 2-inch diameter rock cores "(a)" that represented a condition of joint fracture with a relatively heavy deposit of chlorite and calcite lining the joint faces was cemented together with the polyester resin. The width of the joint was about 1/4 inch. This type of joint and filling was to simulate the probable average condition expected in the field. Two other cores of freshly broken rock ("b" and "c") without any mineral deposits along the fracture faces - one with as narrow a joint as could be obtained, the other with a joint about 1/16 to 1/4 inch in width - were tested for a comparison of bond with fresh rock. In order to test the maximum bonding strength of the polyester resin to the rock under ideal conditions, a core was prepared such that the joint faces were smooth sawed faces in a dry state and the two pieces of core were held together under pressure until the resin hardened. This core ("d") broke at first in tension along an old healed fracture in the rock close to the end of the core with a tensile strength of 79 psi. The core was retested to failure at the bonded joint.

Another core ("e") was made similar to core ("d"), the width of the polyester resin joint was slightly greater (about 1/64 inch), and very little pressure was applied as the resin was hardening. The results of the tensile strength tests are as follows:

Core "a" -	(Chlorite and calcite lined faces wide joint 3/16 to 1/4 inch)	- 133 psi
Core "b" -	(Fresh broken rock, narrow joint 0 to 1/8 inch)	- 216 psi
Core "c" -	(Fresh broken rock, wide joint 1/64 to 1/4 inch)	- 49 psi
Core "d" -	(Sawed joint, surface dry, a very narrow joint, pressure applied)	- 353 psi
Core "e" -	(Sawed joint, surface dry, narrow joint 1/64 inch)	- 249 psi

In all cases, the failure occurred essentially in bond with the rock surface; however, some chlorite and biotite adhered to the resin in the samples in which the surfaces were coated or irregular.

(3) Compressive Strength Tests. Three cores, 2 inches in diameter and 4 inches long, were drilled from one of the rocks. One was broken in compression; a second, which broke transversely at about the midpoint during drilling, was cemented with polyester-resin (width of joint varied from 0 to 1/4 inch) and after hardening was tested in compression. The third core was freshly broken transversely at about the midpoint after drilling, cemented (employing as thin a joint as possible) and similarly tested in compression after hardening. Results of the compression strength tests are as follows:

Core No. 1 -	Solid rock	7,629 psi
Core No. 2 -	Transverse cemented rock (0 to 1/4 inch joint)	8,000 psi
Core No. 3 -	Transverse cemented rock, very narrow joint	7,785 psi

Additional tests were made on two cores to determine the strength of bond of the polyester resin to a smooth sawed, dry rock surface, cut at an angle approximately equal to that of the shear cone planes at time of rupture in unconfined compression. The sawed joint angle was about 32 to 34 degrees from the perpendicular. The 2 by 4-inch cores were placed in a Lucite tube which fitted snuggly around the core, then a small hole was drilled at the bottom of the Lucite container so that it would intersect the bottom of the sawed joint. A close fitting nozzle of a caulking gun was put into the hole and the polyester resin forced into the sawed joint under about 25 psi of air pressure until the resin overflowed the top vent. A similar procedure was used employing a neat portland cement (Type 11) grout using Sika Intraplast-C in an amount of 1 percent by weight of cement. The W/C ratio was 0.36 which provided a grout consistency equivalent to that of thick cream. The core bonded with polyester resin was tested in unconfined compression after 24 hours of hardening, while the portland cement grout bonded core was allowed to cure for 7 days in a humid condition before testing. The core with the polyester resin filled diagonal joint (1/64 to 1/16 inch wide) broke in bond along the joint surface with shear. One vertical crack perpendicular to the sawed joint appeared in the rock also. The core failed in compression at 18,250 pounds total load, which is equivalent to 5,214 psi based on the circular cross sectional (3.5 sq. in.) area of the core. A compressive strength of about 700 psi was obtained for the core cemented together with portland cement grout. This core also broke in bond with shear along the diagonal sawed joint.

(4) Shearing Strength. To a block of rock with an end surface face of about 2.98 by 2.92 inches in size was bonded a layer of polyester resin about 3/8 inch thick. The rock surface to which the resin was bonded had a relatively thick coating of chlorite and mica, typical of a rock joint face. After the resin had hardened for 72 hours, the block of rock was subjected to a compressive load in such a manner that a shearing couple was produced. A total shear load of 690 pounds was obtained at point of failure, which is equivalent to 79 psi based on the surface area of the bonded rock face. The failure occurred at the rock-resin interface, partially in the resin but mostly in the chlorite-mica deposits.

(5) Physical Tests of Polyester Resin.

(a) Tensile and Compressive Strengths. The tensile and compressive strengths of the polyester resin were determined in accordance with ASTM Methods D638-61T and D695-61T respectively. The special apparatus to prevent buckling of the specimen was not used in the compressive strength tests. For the tensile strengths, a flat sheet of resin about 1/8 inch thick was molded and three dumb-bell shaped strip specimens of specified size were cut from it for test. For the compressive strength, small 1/2 inch diameter glass tubes were filled with the resin. After hardening, the tubes were sawed to 1-inch lengths, the glass tube removed, and the resin cylinder ends ground smooth. The test specimens were tested at 73°F after 72 hours of hardening. The test results are as follows:

Sample No.	Tensile Strength, psi
1	5,984 psi
2	5 000 psi
3	6,203
Av.	5,730

Sample No.	Unconfined Compressive Strength, psi
1	12,806
2	12,550
3	12,959
Av.	12,757

(b) Shrinkage. It was discovered during coring of the large chunks of rock bonded together with a thick joint of polyester resin that the resin apparently shrunk from the rock, thereby breaking the bond. A rock sample was sawed in half across the joint and the width of the shrinkage crack measured. The joint gap was 0.37 inches wide and the shrinkage crack, while quite variable, averaged about 0.01 inches. This amounts to about 2.7 percent shrinkage, which compares favorably with a shrinkage value (2.3 percent) obtained from a polyester resin filled vial of 0.82 inch inside diameter, and 3.06 inches long. The vial was slightly overfilled in order to eliminate meniscus effect. Upon hardening, the resin developed a crack at about the middle of the vial which measured about 0.07 inches in width. This value constitutes about 2.3 percent shrinkage. It was also noted that after the polyester resin hardened in a glass tube, it could be easily extruded, indicating that some shrinkage occurs.

b. Second Polyester Resin Test in MRD Laboratory (Lab No. 62/810).

(1) Test Procedure. Five 2-inch diameter granite rock cores were obtained from NORAD, all about 8 to 10 inches in length. The 2-inch diameter core samples of granite rock, which were broken at a prominent joint, were bonded together along the joint plane with polyester resin. The resin was prepared according to the manufacturer's instructions. The polyester resin was applied to both surfaces of the joint face and then the pieces of core were fitted together as closely as possible and wrapped tightly in polyethelene film. After the resin had hardened for 18 hours, the cores were stripped of the polyethelene film and sawed to the desired length of twice the diameter. Two of the broken and recemented cores were tested in compression and two in tension. The one core which was unbroken was tested in tension. The test results are shown in Table 1 and Mohr diagrams of the compression and tensile strengths of the cores are shown by Figures 2, 3 and 4.

(2) Unconfined Compression Strength. All of the compressive strength specimens broke in bond along the polyester resin and the chlorite-coated joint faces in shear along the steeply dipping joint plane, which in one sample was 60 degrees from the horizontal, while the other was approximately 50 degrees. The latter core had the lowest compressive strength (2757 psi) probably because of the smallest surface area of the joint plane and also because it was the most fractured and had to be bonded together in 4 separate planes in order to be tested. The compressive strength obtained on an unjointed core sample tested previously was 7629 psi, whereas the highest value obtained in this series of tests was 4863 psi. This appears to be a reasonable figure for the shearing strength of the polyester resin bond to a chlorite-lined joint and compares favorably with the results obtained previously with bonded sawed joints of approximately the same angle in unaltered rock (5214 psi).

(3) Tensile Strength. Neither of the two cores with polyester resin bonded joints broke at the joint interface with the resin, but rather pulled apart in the rock across the joint, indicating that the polyester resin cemented joint was stronger in tension than the rock sample itself. The average tensile strength of the two cores was 630 psi. The rock cores consisted of a coarse-grained granite with abundant patches of mica. Large crystals of pink feldspar were common. A rock with such a mineral composition and texture is not expected to have a very high tensile strength, so the results obtained are probably reasonable. The unjointed rock core sample tested had a tensile strength of 1112 psi and broke with a cone type fracture within the lower end plate as tested. About two thirds of the core was medium-grained, hard, pink granite; the remaining third was slightly coarse-grained and micaceous.

(4) Mohr Diagrams. Mohr circles were drawn for the compressive and tensile strengths of the cores in accordance with telephoned instructions from Mr. L. S. Bray using in Figure 2 the highest compressive strength (4863 psi) of one of the cores with a polyester resin bonded joint and the tensile strength obtained (1112 psi) for the unjointed rock core. The Mohr envelope drawn tangential to the circles gave an angle of internal friction ϕ of $38^{\circ}40'$. In Figure 3, the lowest compressive strength (2757 psi) of the polyester resin bonded rock core and the average tensile strength (630 psi) of the two jointed rock samples were used for the circles. These gave an angle of internal friction ϕ of $36^{\circ}53'$. In Figure 4, the compressive strength of the rock obtained in a previous test (7629 psi) and the tensile strength of the unjointed rock sample were used for the circles. The angle of internal friction made by the Mohr envelope tangent to these circles was $48^{\circ}22'$.

c. Epoxy Resin, Polyester Resin and Epoxy Bitumen Tests in ORD Laboratory (Technical Report No. 2-31 dated June 1963). The results of the tests in the Ohio River Division Laboratories on three grouting materials for possible use in grouting the A-2 corner at NORAD are contained in Appendix A which is attached. Their report is complete including a summary, conclusions and recommendations, which are not repeated here.

Preparation For Test Injection

4. The results of the laboratory tests were considered to indicate that bonding of the rock with either polyester resin or epoxy resin was feasible despite the coatings which were known to exist on the faces of some of the joint and shear plane surfaces. Final selection was made of Corner No. 3 (northeast) of the A-2 Intersection at NORAD as the location for the first test injection. Reasons for selection were that this corner has shown instability despite the anchor bolts which have been installed, and it also has movement gages installed which it was considered would be useful in observing the effects of grout injection in causing movement of the rock during the grouting operations and in analyzing the effects of the grout in stabilizing movements in the corner after injection. In addition, the corner was known from stratascope observations to contain voids which varied widely in width (0.01 inch to several inches) and to have some voids with surface coatings and other voids without coatings. Arrangements for the test grouting with the two chemical grouts was combined with a contract modification which provided for drilling, washing and grouting a total of 104 holes in the northeast corner of the A-2 Intersection. It was planned to use approximately 12 of these holes for the test grouting program.

The test grouting with chemical grout was kept as a separate item in the contract modification so it could be administered directly by District office personnel who have responsibility for setting up the program and preparing this report. This was also done to facilitate the use of U. S. Bureau of Mines equipment and personnel as well as other experimental equipment provided by a chemical grout manufacturer.

The contract modification provided for grouting an area 50 feet portalward from the theoretical corner on the Pedestrian Adit side and 40 feet from the theoretical corner toward Chamber 3 on the Chamber side, to a height of 40 feet on the wall, on each side of the corner. Injection holes were to be 30 feet deep except in the test area, which was designated as the area approximately 10 feet on each side of the theoretical corner, starting at the floor of the tunnels and extending approximately 15 feet up the wall (See Figure 5). The test area was selected where it was certain that the large shear plane would be intersected by the drill and core holes in less than 18 feet so the U. S. Bureau of Mines stratascope (20' capability) could be used to actually see the conditions in the rock after injection.

In the test area, holes were initially drilled 12 feet deep, with the first 18 inches of the hole from the collar of the rock having a diameter of 1-1/2 inch to accommodate the injection fitting designed by the U. S. Bureau of Mines, and were to be used for injection of both polyester and epoxy resin in the test area. The holes in the test area were later drilled deeper, to 18 feet in the lower row and 24 feet in the upper row, to be certain that the drill holes intersected the large shear plane in this corner. It was considered probable that, after injection of the chemical grouts in the test area, the remainder of the corner would be injected with portland cement grout, which has been the normal method in the past. However, the contract modification was made to provide for three options for the final grouting (portland cement, polyester resin or epoxy resin), and it was stipulated that the Government would select one of the options after the test injection with chemical grouts and exploratory coring to determine the results.

PART II: TEST INJECTION

Purposes of The Test Injection

1. The purposes of this test injection are listed below:

a. Determine the effectiveness of polyester resin and epoxy resin in penetrating the voids in the granite in the A-2 Corner.

b. Study the strength of bond of the polyester resin and epoxy resin to the granite rock as shown in cores removed from the corner.

c. Study the methods and procedures proposed for injection of epoxy resin and polyester resin, determine their effectiveness and make recommendations for possible future work of this type.

d. Study the effects of grouting on movement of the corner and see if the stability of the corner could be improved by chemical grouting.

e. Observe the amount of grout taken and the returns through cracks and anchor bolts.

Drilling and Pressure Washing Test Holes and Calking Cracks

2. The grout holes in the A-2 Corner were drilled with the first horizontal row 5 feet above the tunnel floor. The balance of the holes were drilled in rows at 6-foot intervals both vertically and horizontally. The holes were drilled with an upward inclination of approximately 5 degrees to provide drainage. The holes were drilled with standard percussion drilling equipment. Except for the holes in the test area, the drilling depth was to be 30 feet. If an anchor bar or other steel was encountered, drilling was to be stopped. The depth of the holes is shown on Figure 5. Holes in the test area were initially drilled to a depth of 12 feet and later drilled deeper. In the test area the holes were required to have a diameter of 1-1/2 inches extending from the collar of the hole into the rock for 18 inches to accommodate the injection equipment used for chemical grouting, which was designed and furnished by the U. S. Bureau of Mines.

After drilling, the holes were pressure-washed thoroughly to remove drill cuttings in the hole and to wash cuttings and debris from intersected rock seams as well as possible. The pressures of the air and water used for washing were limited to 25 psi. During the washing operations, water was noted to return from other grout holes (in some cases very remotely located) and from anchor bolts and cracks in the rock.

When pressure washing was completed, the visible surface cracks were thoroughly grouted with a quick-setting cement mortar which was forced into each crack. The larger cracks were backed with jute packing. The drilling and calking operations are shown in Photographs No. 1 and 2, Plate 1.

Injection of Epoxy Resin

3. Injection of epoxy resin was done first because all of the materials and equipment were available for it, before all of the components of the polyester resin arrived. Hole T-1 was injected first, followed by T-2, and then A-8 (See Figure 5). Holes T-3 and T-4 were found to be unsuitable for injection. Holes T-1 and T-2 were drilled to a depth of 18 feet, hole A-8 was drilled to a depth of only 7 feet before an anchor bar was encountered. Hole A-8 appeared to have excellent possibilities for injection, however, since the open, anchor bar hole gave it additional effective length. A 1-1/2-inch pipe 24 inches long was cemented in hole A-8 since it was oversize for the chemical grouting injection equipment. The holes were thoroughly air-blown before injection was started in order to get them as dry as possible. The injection plugs provided by the U. S. Bureau of Mines were inserted and locked in position with their equipment, and injection was started in hole T-1. Photograph Nos. 3 and 4, Plate 2, show the small tilted mixing device (Mix-All type) used to mix the two components of the epoxy resin. Part "A" was emptied into the mixer first and then Part "B" was added while the mixer was in motion. The mixer accommodated a 5-gallon bucket in the turning fitting, and it appeared to do a thorough job of mixing in approximately 90 seconds. The mixed epoxy resin was immediately transferred to the pump reservoir. Photograph Nos. 5 and 6, Plate 3, show the pressure pump which was manufactured by the Alemite Division of the Stewart-Warner Corporation (Model 7835DR). The air pressure control unit was manually adjusted to give the desired gage reading, and the pump produced a pressure at the outlet of approximately 4 times the air pressure. The air pressure was initially set at 25 pounds and later increased to 35 pounds; this would give a pressure of approximately 140 pounds at the pump outlet. The pressure at the collar of the hole was not measured, but was believed to be considerably under 140 pounds since the loss in the 1/2 inch plastic garden hose that carried the resin to the hole and the loss through the injection plug in the hole would reduce the pressure appreciably. The log of injection is contained in Appendix B. A summary of injection data is given in Table 2. As noted in the log of injection for hole No. 1, the surface returns indicated the epoxy resin grout had at least partially filled an anchor bolt approximately 6 feet to the left, and cracks approximately 2 feet above the injection hole showed substantial flow. Later examination of core hole No. 1 between hole T-1 and T-2 showed several cracks ranging from hairline width to 0.8 inch were filled with epoxy resin in this area.

Hole T-2 took more grout than hole T-1 (8.5 gallons for T-1 versus 14 gallons for T-2). It showed a surface return near hole T-1 and returns from anchor bolts approximately 3 feet away and 45 degrees up to the right and to the left, and from one anchor bolt 45 degrees down and to the left. Cracks in surface patches also showed grout returns at a point 3 feet below the hole.

Hole A-8 took a large volume of grout (26 gallons) which was probably due to its intersection with an open anchor bolt hole. Two anchor bolts approximately 9 and 10 feet to the left showed returns, also holes T-3 and T-4 (12 and 6 feet away). Returns were noted from a crack 5 feet to the right and also from cracks approximately 10 feet to the left, showing that the material was penetrating well. The substantial number of cracks that were found to be filled with epoxy resin when core hole No. 2 was examined, including one void between 3 and 5 inches in width, substantiate the fact that penetration was good. The presence of filled cracks immediately adjacent and as close as 1/2 inch to unfilled cracks in the core hole indicates that the cracks are not all interconnected even in this liberally vented rock. Photograph No. 5, Plate 3, shows the injector pump. The pressure gage for the expandable hydraulic sealing injection nozzle is shown at the left. Picture No. 6, Plate 3, shows the expandable, hydraulic injection nozzle or packer at the left during purging operation. This gives a false impression of the maximum rate of flow which was actually under 0.3 gallons per minute average for this test. Photograph Nos. 7, 8, Plate 4 and 9, Plate 5 show the equipment during injection. Note the cloth which was used with jute and wooden plugs to stop leaks. Photograph No. 9 shows the severe leak approximately 5 feet to the right of injection hole A-8 which was very difficult to plug.

Injection of Polyester Resin

4. Injection of the polyester resin was attempted in a total of six holes, two of these holes did not take the grout. The remaining holes each had a very substantial take as shown in Table 2. The equipment for injection of the polyester resin was all furnished by the U. S. Bureau of Mines and it was experimental equipment they have developed for grout injection. The pump was a single-acting, manually controlled, air pump. The air pump drove two separate piston pumps for injection which were sized to handle the grout separately on a 15:1 ratio. Each piston pump was supplied from a mounted reservoir which fed the piston by gravity. Each piston discharged through a high pressure hose to the injector head. Mixing of the base and catalyst took place in the injection fitting seated in the rock by a swirling action before the material was forced through the fitting on into the hole. The expanding, hydraulically operated, packer was used to position and lock the nozzle in the hole. A fluorescent powder was mixed with the polyester resin to facilitate identification of the material by the use of a fluorescope during examination of the cores.

As shown in Photograph Nos. 10, 11 and 12, Plates 5 and 6, the injection pump was mounted on a flat bed truck for convenience. The components of the resin were pumped out of the barrels into buckets and proportioned, and the dye was mixed with one component before the materials were placed in the reservoirs mounted on the pumps. As indicated in Appendix B "Log of Injection," a promoter was used during the initial phase of the test injection to speed up the set and assist in sealing off returns to reduce the loss of resin during injection.

The larger amount of polyester resin available for injection was fortunate because some of the holes in the test area were found unsuitable and the larger holes in the remaining area had to be used. The larger holes required more grout for just filling the hole as shown on Table 2. The lower viscosity of the polyester resin (approximately 2,000 centipoises) probably also contributed to the increased take.

The first hole injected was A-7. The log of injection, (Appendix B) mentions the surface returns. This hole was $2\frac{1}{2}$ inches in diameter and 30 feet deep. The returns, by the time injection was completed, showed a circular pattern around the injection hole with a ~~diameter~~ radius of approximately 2 to 3 feet. The returns appeared first below the hole 2 feet away and slightly left and later developed below and to the right of the hole. The anchor bolts approximately 45 degrees up to the left and to the right of the hole and approximately 3 feet away both showed grout returns, and returns were noted from cracks directly above the hole ranging from 1 to 2 feet distant. Approximately 44 gallons were pumped into this hole in 61 minutes, with little resistance, which indicated that the hole was well vented and reasonably good penetration was being obtained. The returns were well distributed radially around the hole which indicated that good distribution was obtained. The pressure at the pump was estimated at 100 psi for this hole.

Hole No. B-7 was the second hole injected with polyester resin. This hole was $2\frac{1}{2}$ inches in diameter and it had a 30-foot depth. As shown in Table No. 2, 40 gallons of polyester resin were pumped into this hole in 36 minutes before the grouting operation was stopped because movement was noted on one of the movement gages (No. P-19) installed in this corner. The first surface return developed 16 minutes after injection was started. This was in a crack 2 feet below the hole and slightly to the right, after 16 gallons of resin had been injected in this hole. Surface returns showed around an anchor bolt 24 feet to the right approximately 24 minutes after pumping started. At this same time, a return developed one foot directly above the hole. Before shutdown, surface returns were noted 8 feet to the left and slightly below the elevation of the hole. This was after 29 minutes of pumping, and also surface returns were noted in a crack 45 degrees up to the right and approximately 4 feet from the injection hole. This hole was considered to take grout well and to show a good distribution of returns. When rock movement was indicated, the hole still had not shown much resistance to pumping. Injection was stopped immediately on notification that rock movement was indicated.

Hole T-8 was selected as the next hole for injection, when work was resumed on the following day (10 May 1963). Selection was based on the fact that this hole was the greatest distance of any hole in the test area from the last hole injected. It was believed that injection of grout in this hole was least likely to cause rock movement to resume. During grouting of this hole, the injection pressure was held at a lower value (estimated at 50 psi at the collar), and the rate was reduced. This was done as an additional precaution against causing further movement. Hole T-8 had a diameter of $1\frac{1}{2}$ inches and a depth of 24 feet. The wide range of surface returns during grouting of this hole are shown in Photographs starting with No. 12, Plate 6 and continuing through No. 14, Plate 7. The injection hole can be identified in each photograph by the location of the injection nozzle. Surface returns were noted from at least four anchor bolt holes as far as 8 feet from the point of injection and from cracks predominately at elevations above the hole. Surface returns were noted from approximately 20 locations around the hole. This hole took approximately 78 gallons of grout during the 227 minutes of injection. It is considered that this hole was extremely well vented and that distribution of the grout was especially good.

Injection was attempted through the fittings that had been placed in holes B-8 and T-6, but neither hole would take grout. It is probable that these holes had been filled during grouting of adjacent holes.

Hole B-10 was the last hole to be injected with polyester resin grout. It had a diameter of $2\frac{1}{2}$ inches and a depth of 30 feet. Hole B-10 took 37 gallons of grout during the 82 minutes of injection. Six of the anchor bolts in the vicinity of hole B-10 showed returns, with these bolts ranging from 3 to 12 feet in distance from the injection hole. Approximately 12 locations showed grout returns during injection of this hole. This hole showed largely horizontal distribution of surface returns. Possibly this was because the area above the hole had been grouted during previous injection, and the area below the hole is believed to be reasonably free of cracks.

Movement Measurements During Grouting

5. Injection was started in hole B-7 at 11:21 A.M. on 9 May 1963, and at 11:57 A.M. movement was indicated on gage No. P-19 which is located near the injection hole. Injection was immediately stopped. A small disturbance was noted shortly afterward on other movement gages located in this corner. Movement of any appreciable magnitude appeared to have stopped by the following day.

The ease with which movement can be started in this corner is considered to be an index of its instability. This experience prompted a reduction of pressure and the rate of injection for subsequent holes. The movement gages in this corner consist of deeply anchored steel bars encased in steel pipes which contact a micrometer in a sealed case at the rock surface. The movement is measured between the anchor, deep in the rock (approximately 35 feet), and the rock surface.

A tolerance for movement during grouting of a change per hour not to exceed 0.005 inch was established prior to starting the grouting; when this tolerance was exceeded, grouting was to stop. During injection of grout in hole B-7, gage P-19 showed a movement of approximately 0.125 inches before it went off the scale and was reset.

During grouting of the remaining holes, no appreciable change in reading of any of the gages was noted.

PART III: EVALUATION OF TEST GROUTING

General

1. Evaluation of the test grouting presented a problem for a number of reasons; first, the time available did not permit a sufficient period of time for the epoxy resin to fully cure (harden) before coring; second, during laboratory tests, samples bonded with polyester resin had broken when cored even under the controlled conditions in a laboratory; and, third, no precedent was available to establish guidance on testing and evaluation. The variable conditions which can be encountered within a small area in the rock also made it difficult to select any typical condition. Evaluation of cores alone from holes drilled in a variety of locations was anticipated as having a limited value because of the poor condition of the cores after recovery. However, a combination of visual examination of the cores and examination of the core holes with the U. S. Bureau of Mines stratascope, using methods of stratascope observation the Bureau has developed, and possible tests on any bonded cores that were recovered intact appeared to provide a feasible means of evaluation.

Core Drilling

2. Core drilling was accomplished with conventional rotary diamond drilling equipment using NX size bits and equipment. The drill was mounted on a Hyster unit and means were developed to steady the equipment by chaining it to the wall and supporting it from underneath to reduce vibration. Even with these precautions, the vibration during drilling because of the distance from the drill to the wall was very damaging to the cores, so most of the information was obtained from the stratascope examination of the cores conducted by Mr. Oitto of the U. S. Bureau of Mines. The locations for drilling the cores were selected by Mr. H. B. Erickson assisted by Mr. C. W. Livingston, a mining consultant at the NORAD project. The holes were placed near injection holes and were located to intercept known fractures and voids in the structure. The core drilling operation is shown in Photograph No. 15, Plate 8.

Examination of Cores Visually and With Fluoroscope

3. A dye - Calcofluor HEB yellow was added to the polyester resin to aid in its detection with the fluoroscope and to distinguish it from epoxy resin. The epoxy resin had a natural fluorescence in a different color. The boxed cores were first examined at night with the fluoroscope, and the locations which fluoresced were marked on the core boxes. Later the cores were examined visually in daylight. Since the cores were badly damaged during drilling, the width of cracks could not be determined accurately, and it was difficult to identify the exact penetration of the bonding material in some narrow cracks. The stratascope logs of the

cores in Appendix C show the bonding material identified during the core examination by an asterisk in front of the description of the crack.

Examination of Core Holes With Stratascope

4. The large stratascope provided by the U. S. Bureau of Mines was used by Mr. R. H. Oitto of the Bureau to examine and log the NX core holes. The result of the stratascope examination is given in the stratascope log in Appendix C. The locations of the core holes are given on Figure 5. Mr. Oitto is shown using the stratascope in Photograph No. 16, Plate 8.

a. Core Hole No. 1 was located between injection holes No. T-1 and T-2 where the epoxy resin was injected. The log shows a large number of cracks, most of them were very narrow; several cracks were found to contain epoxy resin at depth of 6 to 7 feet from the collar of the hole.

b. Core Hole No. 2 was located 10 inches left of injection hole T-4, which was not used. It was approximately midway between and at the same elevation as injection holes T-2 and A-8. Grout returns in T-4 and in the area where this core hole was placed had been noted during injection, and the stratascope showed a number of the cracks contained epoxy resin and, in the deeper portion of the hole, polyester resin had filled two cracks. At the 5-foot depth, a wide crack 3 inches wide on one side of the core and 5 inches on the other side was found filled with epoxy resin. This core showed rock still bonded to the epoxy although the epoxy had not developed anywhere near full strength.

c. Core Hole No. 3 was located approximately between and two feet below injection holes T-7 and T-8. Polyester resin had been injected in T-8. This hole showed many cracks and most of them contained polyester resin.

d. Core Hole No. 4 was located approximately 8 inches below and 4 inches right of injection hole T-3 which was not used, but grout was noted in it during injection of hole A-8. Core Hole No. 4 was inclined downward at approximately 45° to the horizontal to intersect the large fracture in a minimum distance. It was desired to locate the lower part of the large fracture to see if it was filled with grout. No grout was found, but a large fracture (0.6 inch wide) was intersected 2'-10" from the collar of the core hole. The rock was found to be unfractured below the large fracture.

e. Core Hole No. 5 was located 16 inches to the right and several inches above injection hole T-2. This hole was also drilled downward at 45° from the horizontal. It was intended to check further to see if grout had penetrated the lower portion of the large fracture. The large fracture ($1\frac{1}{2}$ inch wide) was found at a depth of 4 feet, but it had not been filled. Solid rock was encountered below the large fracture.

f. Core Hole No. 6 was located above and slightly to the right of injection hole A-9, which was not used. An epoxy resin return was noted in this area during injection of hole A-8, and it was believed that polyester resin might also show from injection of hole B-10. Stratascope examination of the hole indicated a number of cracks, and two were filled with polyester resin at a depth of approximately $7\frac{1}{2}$ feet in from the collar. One portland cement-filled crack was noted; this was a result of portland cement grouting of the anchor bolts.

g. Core Hole No. 7 was located approximately 2 feet below and to the left of injection hole No. B-10. It was drilled to the right toward the shear plane of the corner. Holes in the first $5\frac{1}{2}$ feet in from the collar of the hole were filled with polyester resin. A crack filled with portland cement grout was noted at 5 feet 10 inches in from the collar.

h. Core Hole No. 8 was located approximately 2 feet below injection hole T-8 and several inches to the left. During injection of hole T-8, which had a high polyester resin grout take, a return was noted in the vicinity of the location of this core hole. A number of the cracks encountered in the core hole were found to be filled with polyester resin. One wide crack (3 inches wide) was found to be filled with polyester resin at a depth of 13 inches. Cracks at a depth of 4 feet were found to contain epoxy resin.

PART IV: CONCLUSIONS AND RECOMMENDATIONS FROM TEST GROUTING

1. Conclusions.

a. Cores. Conclusions from the examination of the cores are as follows:

(1) Examination of the cores indicated that the epoxy resin had developed a much stronger bond to the moist granite than the polyester resin, despite the fact that the epoxy had not had time to harden sufficiently to develop anywhere near full strength when it was cored. Cracks from hairline width to a 3-inch width appeared to be bonded well with epoxy resin. The epoxy resin in the cores could still be marked by a thumbnail at the time it was removed, and the polyester resin in the cores appeared to be fully hardened.

(2) The polyester resin was found in a large number of narrow cracks, but it did not appear to be tightly bonded.

b. Core Holes. Examination of the core holes with the U. S. Bureau of Mines' stratascope gave the best information on the location and width of cracks, and it was possible to see roughly how well filled the cracks were. It was not possible to determine the bond by visual observation. Briefly the following are conclusions from examination of the core holes:

(1) More cracks were filled with polyester than with epoxy resin, but both materials were found in cracks of all sizes ranging from very narrow cracks to medium and very wide cracks.

(2) In some cases, cracks as close as one-half inch to filled cracks were found to be unfilled, which was believed to indicate that the cracks terminate at different points and are not well interconnected.

(3) In some core holes near where extrusion occurred during injection, it was surprising to find that no intrusion of grout in the cracks would be noted except in one or two cracks.

(4) Several severely fractured rock zones encountered showed no penetration of chemical grout.

(5) The items above are considered to indicate that filling of more voids would be achieved by using the greatest number of injection holes possible and keeping the holes of small size to minimize the amount of material required just to fill the holes.

(6) Grout returns from anchor bolts in the vicinity of the test area indicated that the bolts were receiving reasonably large amounts of grout.

c. Materials.

(1) Viscosity. A much greater quantity of polyester resin was used in the test (200 gallons) to 50 gallons of epoxy resin. It was expected that more cracks filled with polyester resin would be found than cracks filled with epoxy resin and this proved true. However, the lower viscosity of the polyester resin, approximately 2,000 centipoises versus approximately 18,000 at the hole temperature (46-48 degrees F.) for the epoxy resin, is believed to account for increased penetration of the polyester resin.

(2) Cost. The cost of the polyester resin from the Contractor was $0.84 per pound for the polyester resin and $1.49 per pound for the catalyst, with a ratio of 15 parts of polyester to 1 part of catalyst by weight, and a cost for placement of $0.28 per pound. This gave the polyester a cost advantage over the epoxy resin which the Contractor charged $1.75 per pound for both the epoxy resin base and catalyst, with a cost of $0.21 per pound for placement. The epoxy resin base and catalyst were said to be sold to the Contractor for approximately $10.80 per gallon which was approximately $1.17 per pound f.o.b. Colorado Springs.

(3) Gel Time and Shrinkage. The polyester resin developed strength much faster and the set time could be adjusted on the job by the addition of a promoter. This would have an advantage in certain situations. The addition of the promoter to get a gel time as low as 10 minutes (can be made even faster) apparently increased the exothermic heat and, consequently, the shrinkage. It is believed that shrinkage of the polyester resin went as high as 7 to 8% for an extremely fast set, versus approximately 3% without a promoter with a 28-minute gel time. The epoxy resin probably gelled at this temperature (46-48 degrees F.) in 4 to 6 hours, but would not have appreciable strength for several days. Its effective shrinkage was said by the manufacturer to be 0.001 percent with a very small exotherm.

(4) Flexibility. As shown in the ORD tests Appendix A, the much greater flexibility of the epoxy resin should make it possible to tolerate movement in the structure without fracturing.

(5) Bond. The excellent bond developed to moist granite by the epoxy resin is considered to be its outstanding advantage over the polyester resin, which showed a poor bond in the cores which were recovered.

(6) Strength. The strengths of both the polyester resin and the epoxy resin in tension and compression are both believed adequate to strengthen most types of rock appreciably. It is necessary to develop good bond to the rock, in addition to having a material with good tensile and compressive strength, if full value is to be obtained from the grout.

2. Recommendations.

a. General. For the final grouting work at NORAD, the epoxy resin was recommended for reasons which will be given at the end of this paragraph; however, neither of the materials tested is considered perfect, and it is hoped that further development work will be done on both materials. It is believed that the epoxy resin would have much better penetration if its viscosity could be reduced to the range of 2,000 to 4,000 centipoises. The polyester resin on the other hand needs improved bonding qualities to moist rock and reduced shrinkage. The reasons for choosing epoxy resin for the A-2 grouting at NORAD were, specifically, as listed below:

(1) Bond. Examination of the cores recovered after the test described herein indicated that the epoxy resin had developed much better bond to the moist granite than the polyester resin.

(2) Shrinkage and Brittleness. Preliminary results of the tests by the Ohio River Division Laboratory given in Appendix A indicated that the epoxy resin was much less brittle and had much less shrinkage than the polyester resin. The ORD Laboratory photoelastic studies also indicated that the epoxy resin did not develop the setting stresses that were found in the polyester resin after hardening.

(3) Equipment. Commercial mixing and injection equipment suitable to handle the epoxy resin was found to be immediately available, and it appeared that there would be several weeks delay in availability of suitable commercial equipment to handle injection of the polyester resin. This office suggested that the manufacturer of the polyester resin make arrangements for suitable commercial equipment which could be readily made available for future work. It is understood informally that this will be done.

b. Future Work.

(1) Drilling. Drill holes should be kept as small as possible to minimize the amount of chemical grout which is required to merely fill the hole. Possibly the depth of holes should be limited so a single length of drill rod can be used wherever possible.

(2) Reinforcing Bars. A reduction in the amount of chemical grant could be effected and a reinforced hole could be provided by placing a suitably sized deformed reinforcing bar in each hole before grouting. A rough cost estimate indicated the purchase of steel specifically for this project at NORAD would have cost more than polyester resin per cubic inch, but probably less than epoxy resin. The U. S. Bureau of Mines has successfully used steel bars in their work and it appears to have merit.

(3) Stage Grouting. There may in some cases be an advantage to injection of chemical grout in two or three stages in one

hole; for example, inject the back one-half of the hole first as Stage 1 using an expandable packer, then inject the front half of the hole as Stage 2 by moving the expandable packer forward to the collar of the hole. Holes would probably need to exceed 12 feet in depth before a second stage would be feasible. The main advantage would be the possible use of greater pressure at the back of the hole to improve penetration. An alternate method might be drilling holes 8 to 10 feet deep, filling them and then drilling deeper holes for a second injection which might be done at higher pressure.

(4) Pressure. Pressure should be measured at the collar of the hole or as near to the collar as possible. The pressure used was dependent on the condition of the rock. In the A-2 corner, extra care was necessary because of the instability of the rock in this corner. The rate of flow of the grout is as important as pressure and must be carefully considered. A maximum and minimum rate of flow should be furnished in the specifications. Movement in the A-2 corner occurred after the corner had received a large amount of grout, at a relatively fast pumping rate, but without any large pressure build-up. It is recommended that the pressure be set initially, using the best judgment possible, considering the condition of the rock as to stability, venting, etc., and the capacity of the pump being used should be included in this consideration. A careful watch should be kept on the collar pressure to see that it does not exceed the desired limit and, also, to watch it build up so the pumping rate may be reduced if necessary. The grout returns should be carefully observed and recorded as the best indication of penetration. Along with the amount of grout injected, this will give the best index of penetration short of core drilling. Adjustments can be made in the maximum collar pressure and rate of injection as the work proceeds. The maximum pressure should be maintained on each hole for not less than 10 minutes after it is obtained to assure penetration.

(5) Maintenance. Gages must be protected from the chemical grouts by a diaphragm and oil column arrangement. This unit and all units such as safety valves, the injection nozzles, and any unit exposed to the chemical grouts must be thoroughly cleaned every few hours and immediately on shutdown. A standby pump and all other equipment must be on the job so injection will not be delayed or a hole lost as a result of equipment failure. All gages must be checked frequently as they tend to become clogged with the hardening resin. The zero point of the gage should be checked frequently, or the pressure indicated will probably be below the actual pressure in the hole. Any pop-off valve that is operated will probably require replacement and thorough cleaning, or it will leak and slow down production. The viscous resin tends to keep a valve from closing once it has been opened.

TABLE 1

U. S. ARMY ENGINEER DIVISION, MISSOURI RIVER
CORPS OF ENGINEERS
DIVISION LABORATORY
OMAHA, NEBRASKA

COMPRESSIVE AND TENSILE STRENGTH
OF 2-INCH DIAMETER GRANITE ROCK CORES

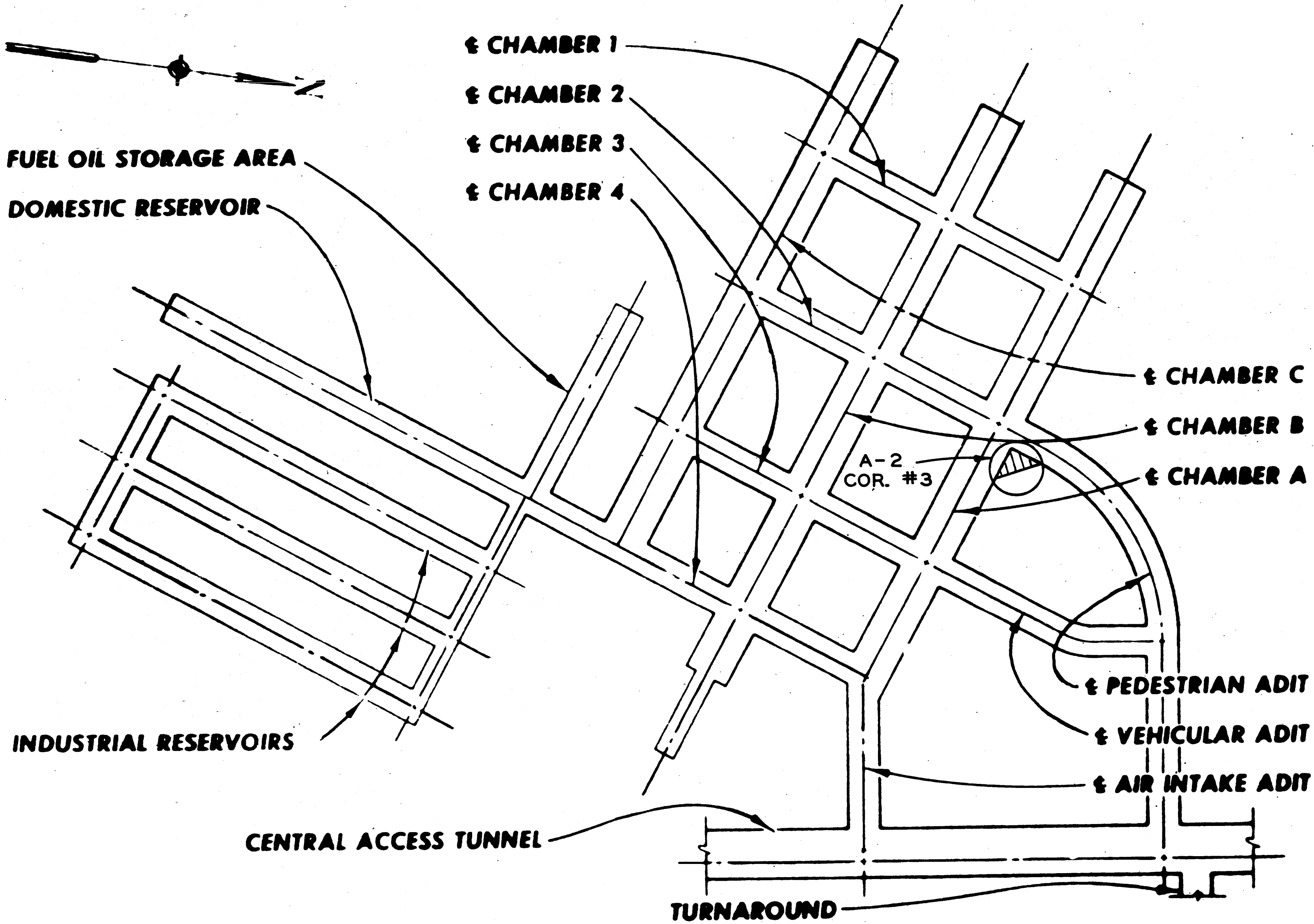
NORAD MRD Lab. No. 62/810

SAMPLE	DESCRIPTION OF FAILURE	DIP OF JOINT DEGREES FROM HORIZONTAL	UNCONFINED COMPRESSIVE STRENGTH PSI	TENSILE STRENGTH PSI
A	Broke across rock in jagged fashion toward lower end of core as pulled.	61		626
B	Broke with cone fracture in rock in upper end plate as tested.	70		635
C	Broke with cone fracture in rock in lower end plate as tested.	No joints		1,112
D	Broke in bond along chlorite-biotite interface of joint; part of failure was in the polyester resin.	60	4,863	
E	Broke in bond along chlorite interface of joint; part of failure was in the polyester resin.	50 (2 parallel joints)	2,757	

TABLE 2
SUMMARY OF INJECTION DATA

GROUT TYPE	HOLE NO. INJECTION SEQUENCE	SIZE INCH	LENGTH FT.	HOLE VOLUME GALS.	TAKE VOLUME GALS.	TIME MINUTES	GPM INJ. RATE	PRESSURE PSI	GALS EST. LEAK LOSS	TAKE GALS. PER/FT. DEPTH	TAKE PER/FT. GALS. LESS HOLE VOL.
EPOXY	T-1	1 1/2"	18	1.65	8.5	36	0.235	140	1/2	0.47	0.38
EPOXY	T-2	1 1/2"	18	1.65	14	51	0.275	140	1/2	0.78	0.69
EPOXY	A-8	2 1/2"	7	1.78	26	128	0.203	140	2	3.72*	3.46*
POLYESTER	A-7	2 1/2"	30	7.65	44	61	0.723	100	4	1.47	1.21
POLYESTER	B-7	2 1/2"	30	7.65	40	36	1.11	100	2	1.33	1.08
POLYESTER	T-8	1 1/2"	24	2.2	78	227	0.343	50	11	3.25	3.16
POLYESTER	B-8	2 1/2"	30	7.65	0	0	0	50	0	0	0
POLYESTER	T-6	1 1/2"	24	2.2	0	0	0	50	0	0	0
POLYESTER	B-10	2 1/2"	30	7.65	37	82	0.45	50	3	1.23	0.98

* HOLE DRILLED INTO AN OPEN BOLT HOLE AND STOPPED. GROUT PROBABLY WENT ALONG BOLT IN ABNORMAL TAKE.



NORAD C.O.C.
COLORADO SPRINGS, COLO.
FIGURE 1

FIG. 2

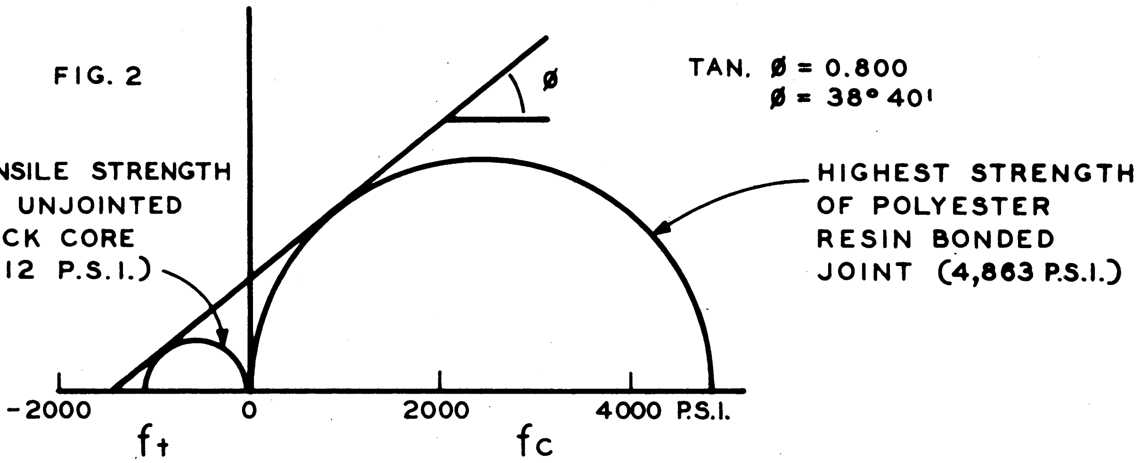


FIG. 3

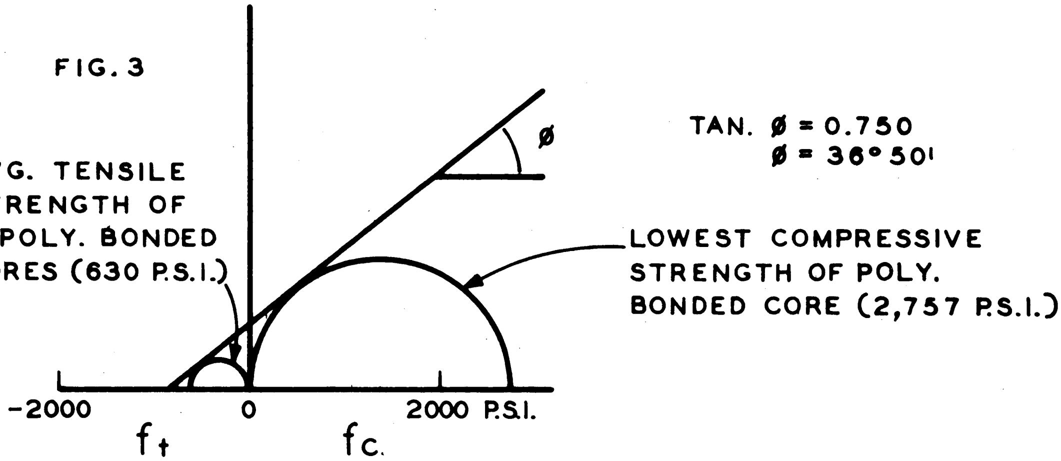
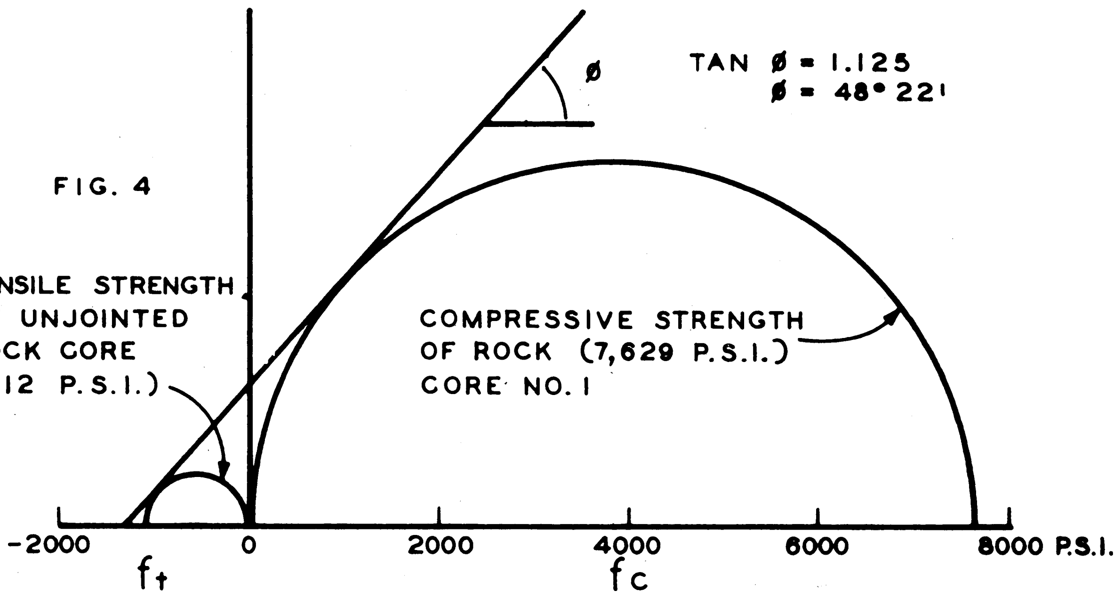
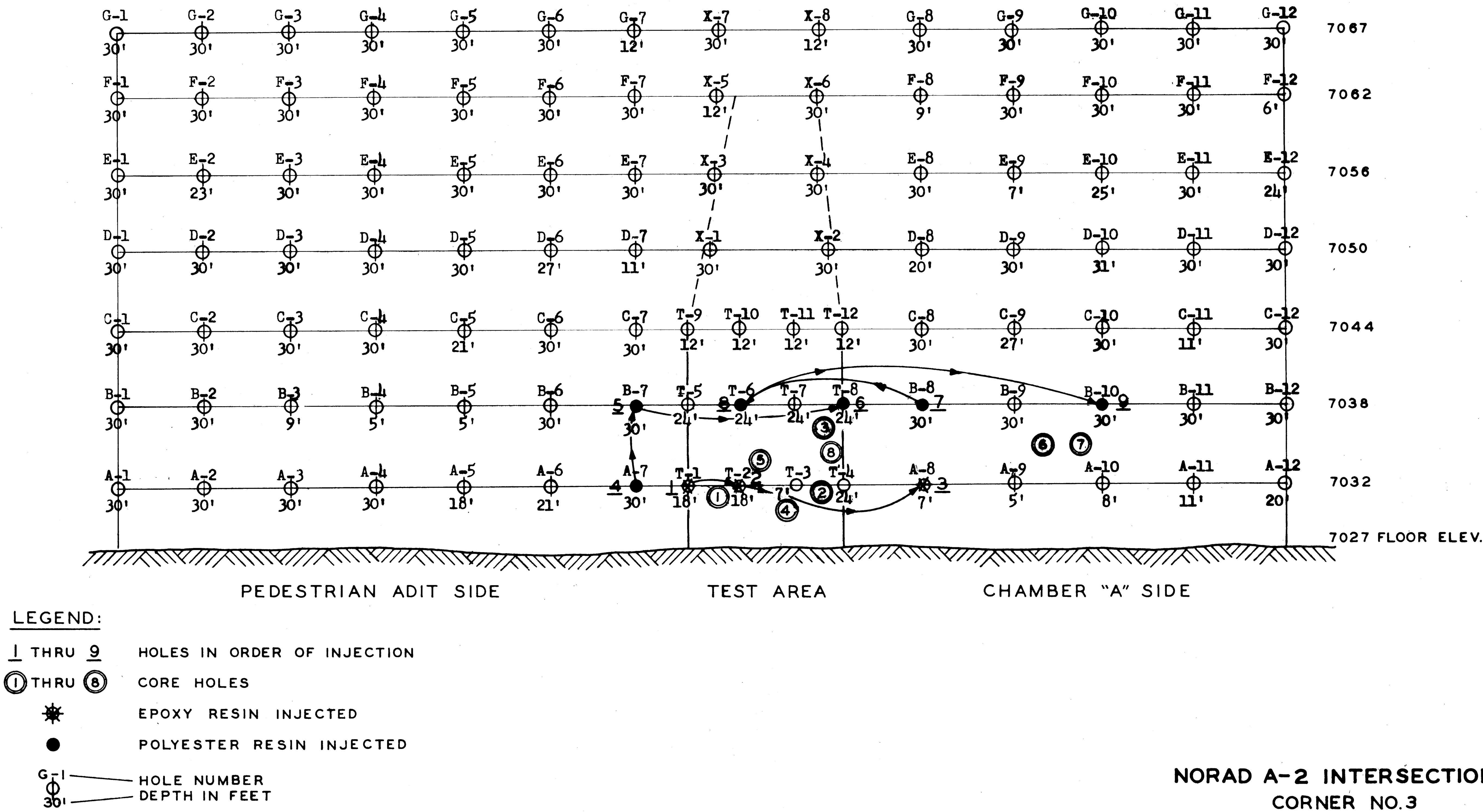


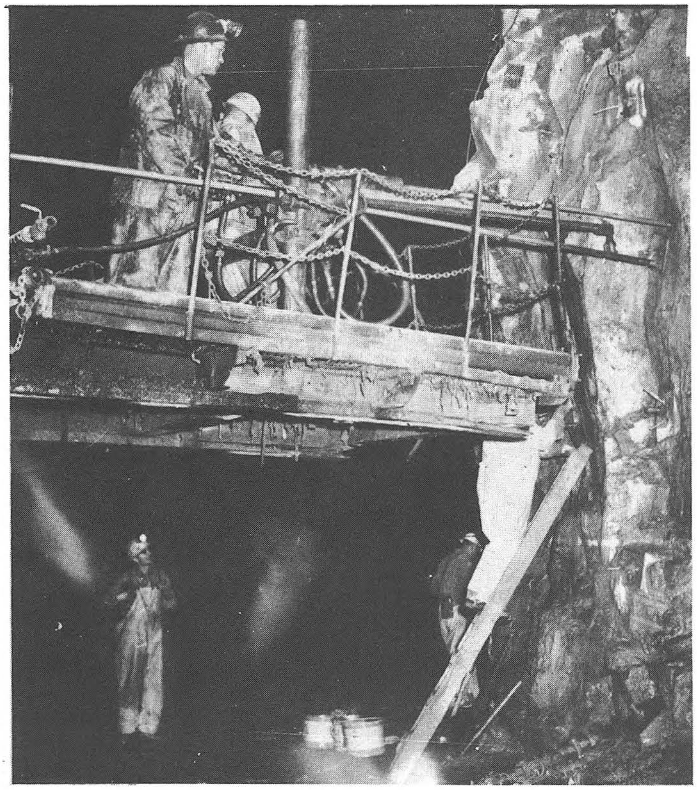
FIG. 4



MOHR DIAGRAMS



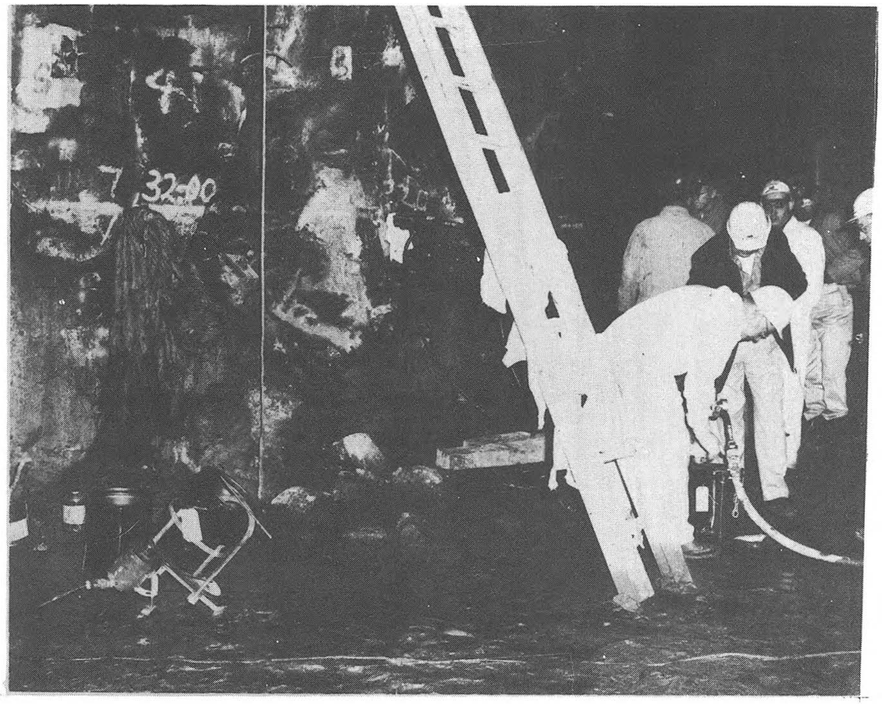
NORAD A-2 INTERSECTION
CORNER NO. 3
HOLE LOCATION
FIGURE 5



Drilling Injection Holes 1

Calking Cracks 2

PLATE I

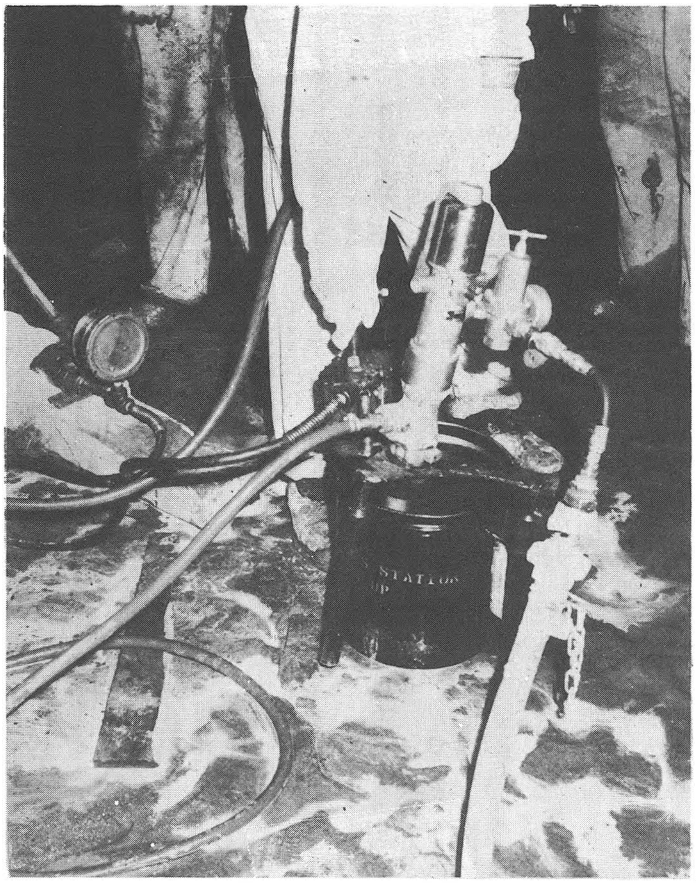


3

Mix-All Type Mixer

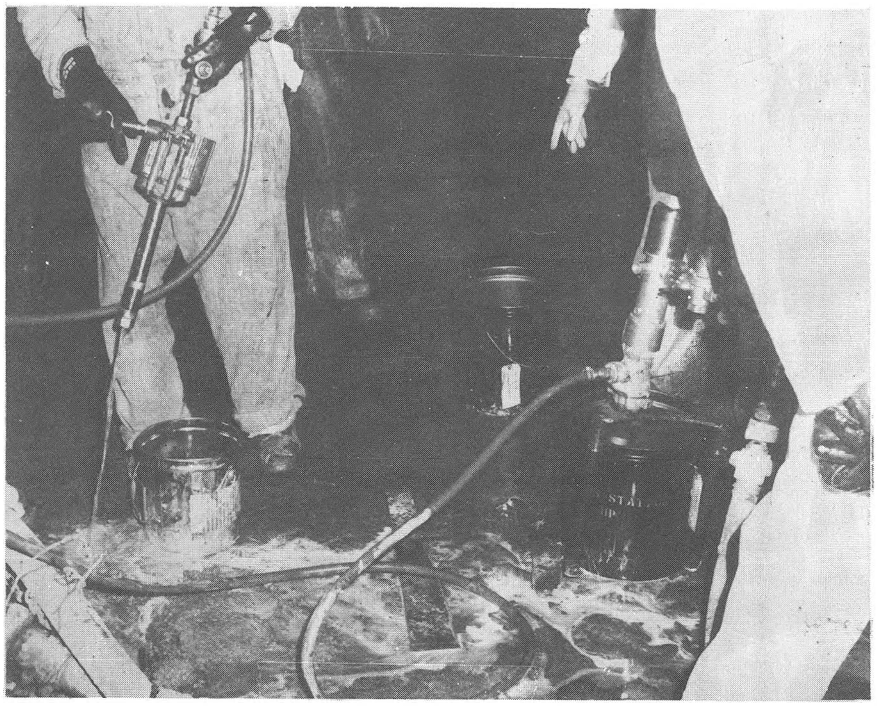
4

Mix-All Type Mixer



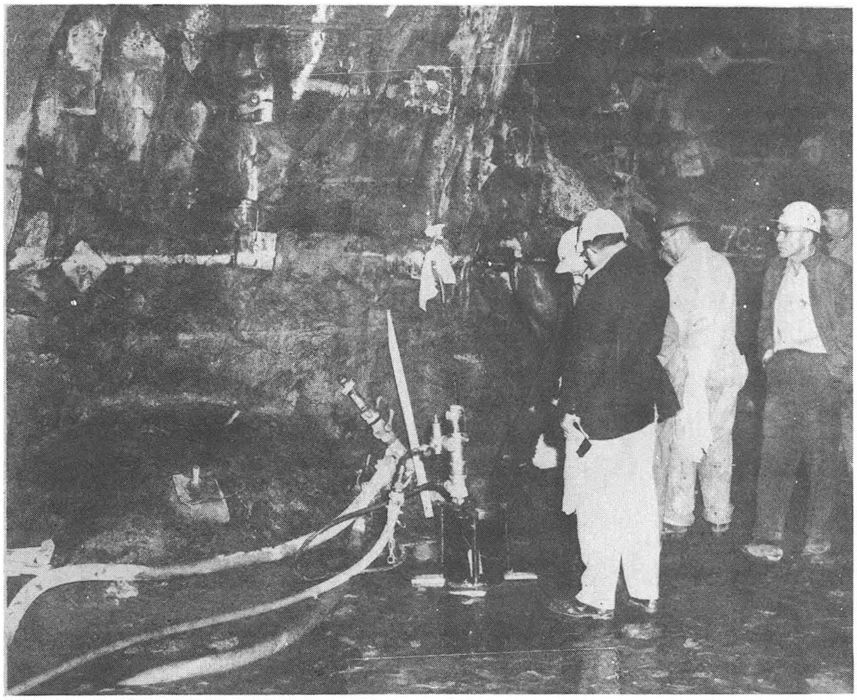
5

Alemite Grout Pump



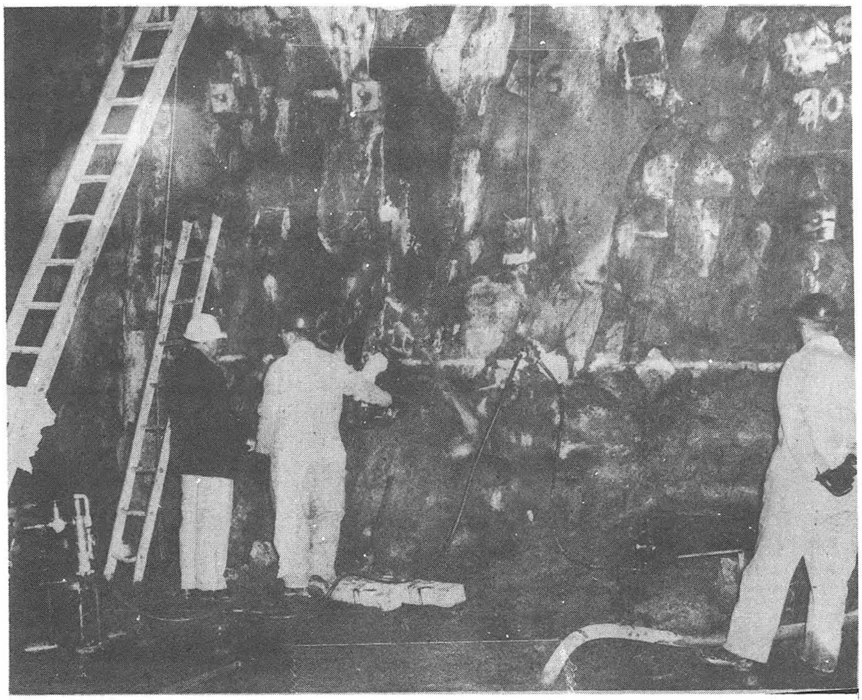
6

Injection Nozzle and Grout Pump



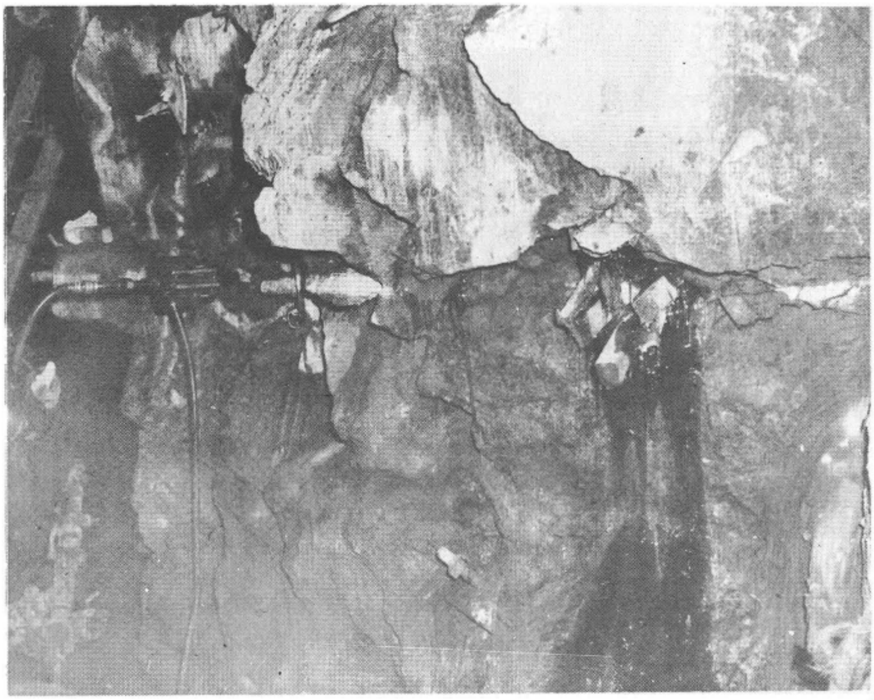
7

Injection Pump and Injection Nozzle in Operation



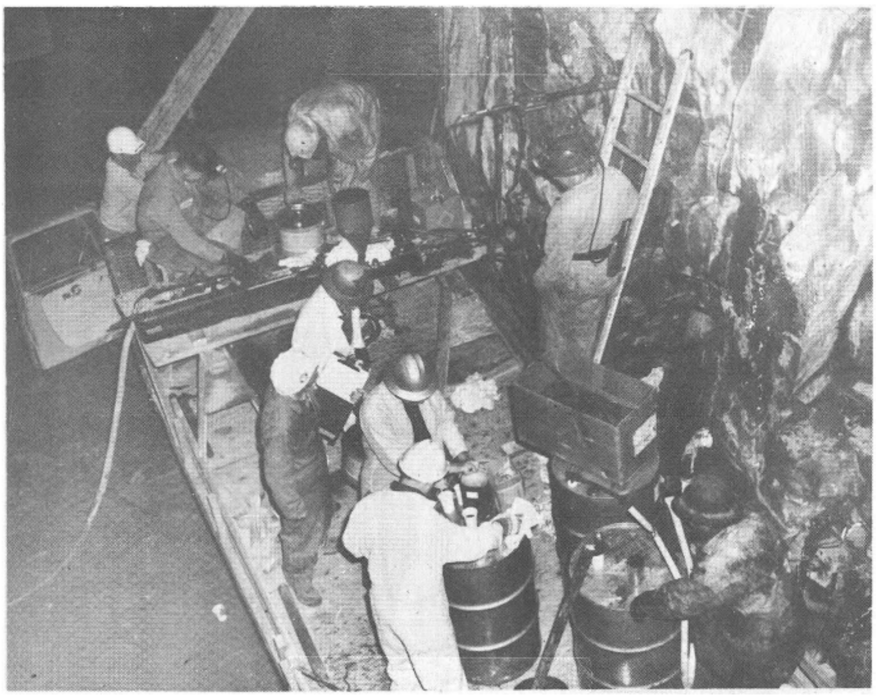
8

Epoxy Resin Injection Operations



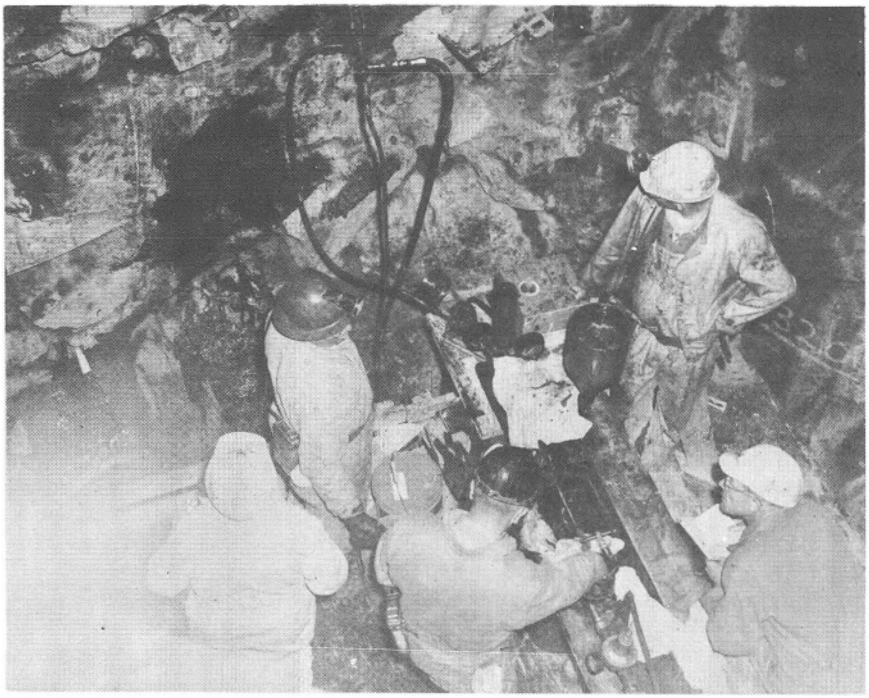
9

Injection Nozzle and Epoxy Extruding From Crack



10

Polyester Resin Injection Operation

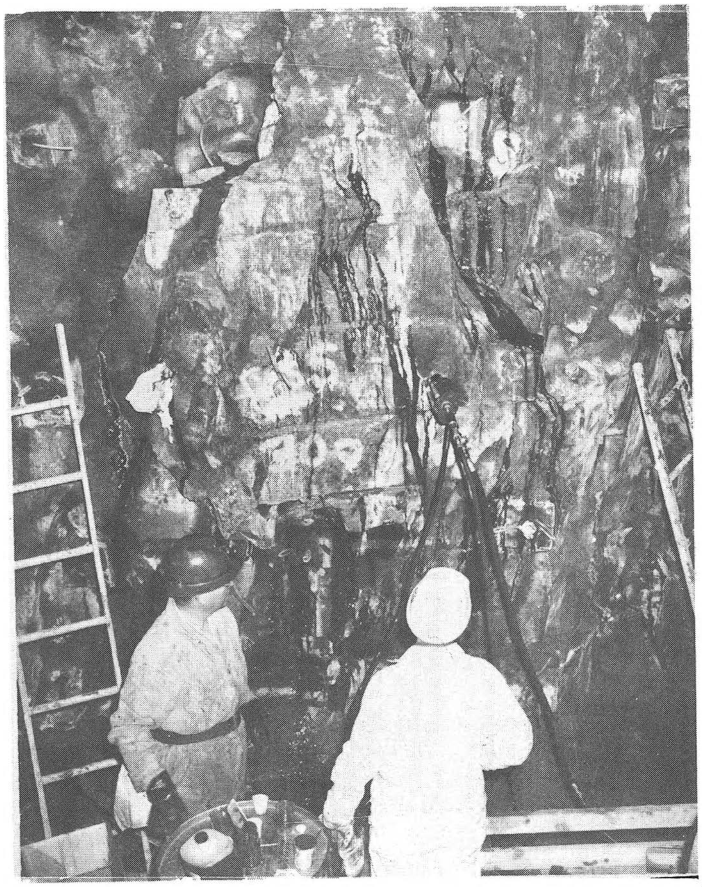


11

Polyester Resin Pump and Injector Nozzle

12

Polyester Resin Grout Returns During Injection of Hole T-8



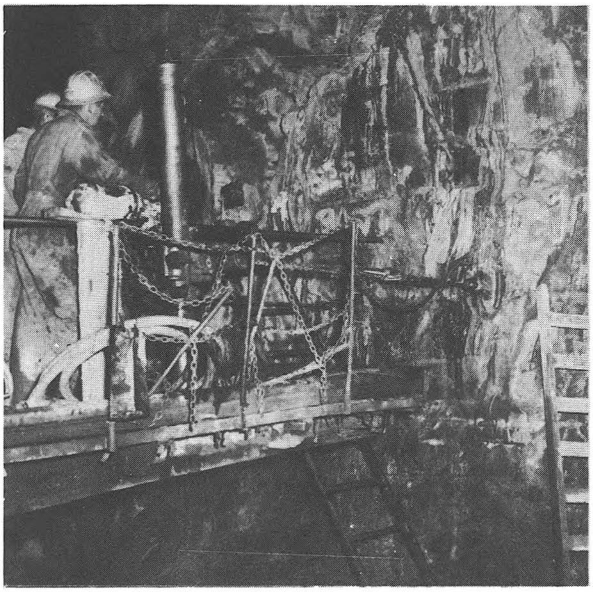
13

Polyester Resin Grout Returns During Injection of Hole T-8

14

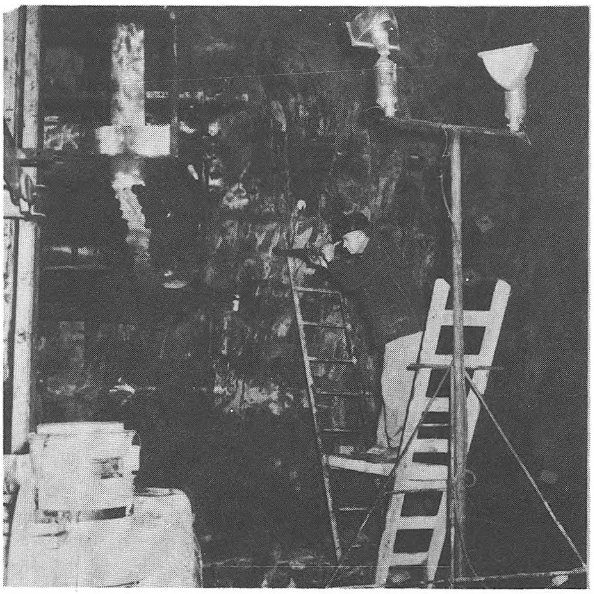
Polyester Resin Grout Returns During Injection of Hole T-8

PLATE 7



15

Diamond Drilling For Evaluation Cores



16

Stratascope Operation

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REPORT OF LABORATORY PILOT STUDIES FOR ROCK BONDING WITH CHEMICAL GROUTS

TECHNICAL REPORT NO. 2-31

JUNE 1963

U. S. ARMY ENGINEER DIVISION, OHIO RIVER

CORPS OF ENGINEERS

OHIO RIVER DIVISION LABORATORIES

CINCINNATI, OHIO

APPENDIX A

REPORT OF
LABORATORY PILOT STUDIES FOR
ROCK BONDING WITH CHEMICAL GROUTS

TECHNICAL REPORT NO. 2-31

June 1963

U. S. Army Engineer Division, Ohio River
Corps of Engineers
Ohio River Division Laboratories
Cincinnati, Ohio

PREFACE

The authority for these studies was contained in the second indorsement of the Chief of Engineers (file ENGMC-EM), dated 17 January 1963, to a letter from the District Engineer, U. S. Army Engineer District, Omaha, dated 30 October 1962, subject, "Proposed Civil Works Investigation - Rock-Bonding with Chemical Grout". Funds for this work were provided by the Missiles Branch, Engineering Division, Directorate of Military Construction, Office, Chief of Engineers.

The studies, reported herein, were conducted at the Ohio River Division Laboratories, under the supervision of Messrs. John M. Merzweiler, Israel Narrow, Belmon U. Duvall, and Verne D. Edgerton. This report was prepared by Mr. Frank M. Mellinger, Director of the Laboratories and Mr. Duvall.

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FIGURES 1 - 6

PLATES 1 - 3

APPENDIX A MEMORANDUM REPORT (Conference 27 February 1963)

APPENDIX B MEMORANDUM REPORT (Conference 13 March 1963)

K E Y

Polyester Resin System

Producer "A"	Wallace & Tiernan, Inc. Lucidol Division 1740 Military Road Buffalo, New York
Producer "B"	American Cyanamid Company 1937 West Main Street Stamford, Connecticut

Epoxy Resin System

Producer "C"	Jones-Dabney Company Div. of Devoe & Raynolds, Inc. Louisville, Kentucky
Producer "D"	George W. Whitesides Company 3048 Michigan Drive Louisville, Kentucky

SUMMARY

The purpose of these studies was to develop information for the consideration of the use of a special epoxy resin system as a chemical grout for rock-bonding at the NORAD project.

The tests were conducted using a polyester resin system, a special epoxy resin system selected after study of the conditions obtaining at the project, and an epoxy-bitumen system. Time available due to construction progress at the NORAD site limited investigational testing to the use of dry-face fractured rock to determine bond strengths developed, ability of the chemical grouts to accommodate movement prior to material or bond failure, and also the compressive and tensile strengths of rock cores from the project area.

The laboratory studies and data analyses disclosed that the specific epoxy resin system had more suitable characteristics for the usage considered than the polyester resin system. Also, the epoxy-bitumen system should be further studied since the cost is less than that of the selected epoxy resin system, being about equal to that of the polyester resin system. Significant information obtained was that although the strengths for the epoxy resin and the epoxy-bitumen bonded cores were lower than those for the polyester system bonded cores, the latter system would accommodate only a relatively low order of movement prior to material or bond failure in comparison with the other two systems.

REPORT OF LABORATORY PILOT STUDIES FOR
ROCK-BONDING WITH CHEMICAL GROUTS

PART I: INTRODUCTION

Objective of Studies

1. The objective of the tests reported herein was to provide additional information for determining the efficacy of rock-bonding with certain chemical grouts (thermosetting plastics). Originally, it was proposed that a polyester resin system should be used; however, on the basis of general information available as to the geology involved and the desirable properties of any bonding medium, doubt was expressed that the polyester resins would be suitable with respect to some properties for the application intended. Under the project conditions, obtaining the use of a specially formulated epoxy resin system was suggested for consideration.

Background

2. In a letter to the Division Engineer, U. S. Army Engineer Division, Missouri River, dated 30 October 1962, the District Engineer, U. S. Army Engineer District, Omaha, proposed a Civil Works Investigation on Rock-Bonding by injections of a polyester resin system chemical grout. The investigation was approved and funded by the Chief of Engineers (ENGMC-EM) by a second indorsement thereon, dated 17 January 1963. This approval also requested, if possible, expanding the test program to include testing of an epoxy resin system and that the Ohio River Division Laboratories be afforded an opportunity to participate in the investigation.

3. A meeting was held at the Office of the District Engineer, Omaha, on 27 February 1963 to brief a representative of the Ohio River Division Laboratories on the proposed testing program and to explore the possible addition of a selected epoxy resin system to the planned test injection of the polyester resin system at the NORAD facility at Colorado Springs, Colorado. During this meeting the possible advantages of using the epoxy resin system were presented and a series of comparative pilot laboratory tests, using fractured rock cores from NORAD and both resin systems, was suggested by the Ohio River Division Laboratories representative. These tests were subsequently approved by the Director, Ohio River Division Laboratories, and the necessary cores furnished by the Omaha District. The proposed polyester resin and epoxy resin materials were obtained by Ohio River Division Laboratories from the producers cooperating in the test program. A conference report of the meeting was prepared by Omaha District (MRHGF) personnel, subject, "Conference on Proposed Polyester and Epoxy Grouting at NORAD", dated 28 February 1963 (Appendix "A"). This report presents in paragraphs 3.b. (b), (c), and (d) some of the advantages which might be anticipated with the use of the epoxy resin system that, possibly, would not obtain with the use of the polyester system.

4. A second meeting was held at the Omaha District Office on 13 March 1963 for the purpose of obtaining further information and clarification on the properties of the specific polyester resin system proposed by the producer for the NORAD tests. A conference report on this meeting was also prepared by Omaha District personnel, subject, "Conference on Polyester Resin Grouting NORAD - Contract DA-6693", dated 15 March 1963. A copy of this report is attached (Appendix "B").

PART II: LABORATORY TESTS

Program

5. The scope of the Ohio River Division Laboratories pilot tests was of necessity limited due to (1) the short time interval between the decision to proceed with the field test and the NORAD project completion date for areas where such tests were feasible, and (2) funds available for further laboratory testing. The program established was such as to provide only indicative and comparative data on the following facets:

a. Ability of the resin systems to bond to weathered fractures in the rock.

b. Effect of rock fracture angle on strength of the resin bonded rock cores.

c. Ability of the resin bonded rock fractures to accommodate movement prior to failure.

d. Compressive and tensile strengths of typical rock cores.

6. Circumstances permitting, it would have been desirable to conduct these laboratory rock-bonding tests on both wet and dry rock faces. The ability of certain epoxy resin systems to bond to various substrates in the presence of moisture has been well established, but this same property of polyester resins has been subject to question. The representatives of the polyester producer gave assurance that the particular polyester system proposed for use in these tests would give high bond if moisture was present; therefore, in view of the time urgency, only dry face tests were included in the test program.

Materials

Chemical Grouts

7. Samples of the special formulations of the two resin systems proposed for use as chemical grouts were obtained from the producers.

These were identified and described as follows:

Polyester Resin System (Two-components)

PART "A" (Polyester Resin)	-	A polyester resin containing about 30 percent styrene monomer, manufactured by Producer B.
PART "B" (Catalyst)	-	A peroxide type catalyst, manufactured by Producer A.
PROMOTER	-	None
PROPORTIONS	-	15:1 (Polyester:Catalyst), by volume

Epoxy Resin System (Two-components)

PART "A" (Catalyst)	-	A polyamide resin manufactured by Producer C, and modified in formulating by Producer D.
PART "B" (Epoxy Resin)	-	A bisphenol A - Epichlorohydrin based epoxy manufactured by Producer C, and modified in formulating by Producer D.
PROPORTIONS	-	4:1 (Epoxy:Catalyst), by volume

The general physical properties and the test methods employed in determining these properties are given in Table 1.

Table 1

PHYSICAL PROPERTIES OF THE CHEMICAL GROUT SYSTEMS

Property	Epoxy Resin System		Polyester Resin System	
	Value	Test Method	Value (1)	Test Method
Tensile Strength, psi	5,100	ASTM D 638-58T	8,100	ASTM D 638-58T
Tensile Modulus	0.17×10^6	ASTM D 638-58T	---	---
Elongation, percent	15.8	ASTM D 638-58T	2.6	ASTM D 638-58T
Flexural Strength, psi	8,700	ASTM D 790-59T	12,300	ASTM D 790-59T
Flexural Modulus	0.21×10^6	ASTM D 790-59T	0.62	ASTM D 790-59T
Deflection, inches	0.53	ASTM D 790-59T	Not reported	---
Compressive Strength, psi	7,500	ASTM D 695-54	Not reported	---
Compressive Modulus	0.19×10^6	ASTM D 695-54	Not reported	---
Deflection at Yield, inches	0.18	ASTM D 695-54	Not reported	---
Izod Impact Strength (ft. lbs./in. of notch)	0.82	ASTM D 256-56	Not reported	---
Hardness of 77° F (Shore D)	79	ASTM D 1706-59T	38-40 (2)	---
Water Absorption, percent	0.21	ASTM D 570-59T	0.15	ASTM D 570-59T
Shrinkage, percent (Volume)	0.001 (3)	Not reported	6.0	Not reported

(1) Typical values

(2) Barcol

(3) Effective (after gel formation)

Rock Cores

8. Four groups of NX core samples from the NORAD site were furnished to the Ohio River Division Laboratories by the Omaha District. These groups were:

a. Six cores having fractures at about 25° from the horizontal.

b. Six cores having fractures at about 45° from the horizontal.

c. Six cores having fractures at about 60° from the horizontal.

d. Three cores having no visible fractures, and one core having a recemented joint 70° from the horizontal.

A summary of the Core Logs furnished with samples is given in Table 2, following PART VI of this report.

Procedures

9. There are no known standardized procedures for obtaining the information desired in this pilot test program. Therefore, specimen preparation techniques and testing procedures were devised which utilized recognized basic principles to provide comparative test data in the areas under consideration.

10. In order to maintain proper alignment of the two sections of the fractured cores when bonding was being accomplished, snug fitting "Lucite" tubing was used as a mold. As shown in Photograph (a) of Plate 1, the tubing was drilled near each end and tapped so that screws could be used to hold the core sections in-place and maintain an approximate 1/8-inch separation to accept the chemical grouts. A larger hole was drilled through the tubing over the fracture to permit introducing of the chemical grouts. The ends of tubing were closed using overlapping strips of adhesive-backed vinyl tape.

11. Approximately 180-gram batches of the properly proportioned,

two-component, chemical grouts were hand-mixed in 400 ml breakers, for 90 seconds, permitted to stand undisturbed for 5 minutes, then the void between the core sections filled. This was accomplished by using a polyethylene nozzle inserted in the hole in the "Lucite" tubing over the 1/8-inch maintained separation of the core sections. It was initially believed that the use of an air actuated pressure caulking gun, as shown in Photograph (b) of Plate 1, would be necessary to fill the voids; however, trials showed that the viscosity of the grouts was sufficiently low that gravity feed was adequate.

12. After filling the voids with chemical grout, the specimens were cured at 75° F for 7 days. The "Lucite" tubing was then split by sawing longitudinally at opposite points on the circumference to permit removal of the bonded cores (Photograph (a), Plate 2). Owing to the non-chemically clean polished inner surface of the tubing, except in one instance, no difficulty was experienced in removing the cores due to any high bonding of the grouts to the tubing. Core No. 12 (45° angle fracture) used in the polyester test group separated at the planned bond line during the sawing of the tubing. This may have been due to the shrinkage of the polyester grout since the bonding seam, due to edge chipping possibly during coring, varied in thickness with the maximum thickness being about 5/16-inch (Photograph (a), Plate 2). A group of the bonded cores and two of the non-fractured rock cores are shown in Photograph (b), Plate 2.

13. Movement gages were attached to the upper and lower sections of the aged bonded cores as shown in Photograph (a), Plate 3, and the compression load applied at a rate of 1,000 pounds per minute. Movement readings were taken at each 500-pound increase in load. Similar tests were made on the four cores without visible fractures. In testing of some of the epoxy resin bonded cores, when the load gage failed to show any increase in load due to movement of the core sections, i.e., slip along the bond line or movement accommodation without rupture, the load application was released. After 120 seconds had elapsed the movement gages were again read to note recovery.

14. Tensile strength tests were also made on three NX cores which had no visible fractures. The cores were cemented in metal grips with an epoxy resin, aged 24 to 36 hours at room temperature, and tested in tension with the load being applied at the rate of 300 pounds per minute. A typical specimen set-up for this testing is shown in Photograph (b), Plate 3.

PART III: TEST RESULTS

Compression Tests of Bonded Cores

15. The results of the compression tests of the chemical grout bonded cores are shown in Table 3.

Table 3

Core No.	Bonding Medium	Fracture Angle, 0°	Compressive Strength, psi	Movement, inches
13	Epoxy Resin (1)	20	8,220	0.0813
14	Epoxy Resin (1)	20	7,960	0.0211
15	Epoxy-Bitumen (2)	30	4,960	0.0455
17	Epoxy-Bitumen (2)	25	6,110	0.0816
16	Polyester Resin (3)	20	8,155	0.0178
18	Polyester Resin (3)	25	13,480	0.0163
7	Epoxy Resin	45	2,960	0.0790
8	Epoxy Resin	35	4,315	0.0641
9	Epoxy-Bitumen	50	2,225	--
10	Epoxy-Bitumen	45	2,820	0.0455
11	Polyester Resin	45	6,170	0.0090
12	Polyester Resin	45	--	--
1	Epoxy Resin	60	2,450	0.0797
2	Epoxy Resin	55	2,830	0.0218
3	Epoxy-Bitumen	60	1,415	0.0538
4	Epoxy-Bitumen	60	1,860	0.0411
5	Polyester Resin	55	6,730	0.0062
6	Polyester Resin	60	4,325	0.0225

(1) None of the epoxy resin bonded specimens completely failed in either shear at the bond line or failure of the rock. When the load being applied at a constant rate failed to show an increase in total load due to continued movement at the bond interface, loading was released. Movement readings continued for 2 minutes thereafter showed approximately a 50 percent recovery from the total movement that had occurred.

(2) The epoxy-bitumen bonded specimens were included in the tests for information only. At this time, overall data on the material are believed inadequate to consider use of the epoxy-bitumen system for the purpose being studied.

(3) All of the polyester resin bonded specimens failed completely in shear along the bond lines.

16. The above data, including rate of movement with increased load applied, is shown graphically in Figures 1 and 2. No graph was prepared for the epoxy-bitumen bonding tests.

17. The results of the compressive strength tests of four NX cores having no visible fractures are shown in Table 4 below:

Table 4

Core No.	Compressive Strength, psi
14	+ 15,450 (1)
19-1	10,320
19-2	+ 15,450 (1)
20-1	13,500 (2)
20-3	15,000

(1) Limit of testing machine used.

(2) NX Core had a re-cemented joint 70° to the horizontal.

This data including movement as load was applied are presented graphically in Figure 3.

Tensile Strength of Rock

18. In order to assist in an analysis of the over-all test data, tensile strength was determined on three of the NX cores furnished from NORAD. The results of these tests are shown in Table 5 below:

Table 5

Core No.	Tensile Strength, psi
14	1080
15	700 (1)
16	1065

(1) Specimen not properly aligned.

PART IV: DISCUSSION AND ANALYSIS OF TEST RESULTS

General

19. A comparison of the results of tests with the three chemical grouts, used in bonding rock cores with fracture planes (three groups averaging 24°, 44°, and 58° to the horizontal), rates these systems with respect to compressive strength in the order that would be anticipated on the basis of the properties of the chemical grouts alone. The following Table 6 contains a summary of the average compressive strength data (Paragraph 15) grouping the bonded cores with respect to variation in fracture angle, and for ease in comparison rating the epoxy-bitumen group as 1.000:

Table 6

Chemical Grout	Fracture Angle					
	24°		44°		58°	
	Comp. Str., psi	Rating	Comp. Str., psi	Rating	Comp. Str., psi	Rating
Epoxy-Bitumen	5535	1.000	2525	1.000	1640	1.000
Epoxy Resin	8040	1.453	3640	1.442	2640	1.609
Polyester Resin	10820	1.955	6170	2.404	5530	3.372

This summary clearly shows the effects of the inherent strength of the three chemical grouts tested.

20. In discussions of the over-all project objectives for which these studies were made, it was suggested by the Ohio River Division Laboratories representative that any chemical grout system employed should

attain reasonable strengths and have the ability to accommodate some movement of the rock mass without complete failure in either bond or shattering of the chemical grout layers due to brittleness. In analyzing the data presented herein (See Paragraphs 15 and 19, and Figures 1 and 2), it will be noted that regardless of fracture angle the polyester resin bonded cores showed the highest compressive strength; the epoxy resin group, the intermediate strengths; and the epoxy-bitumen group, the lowest strengths. However, the average ability of the chemical grouts to accommodate movement prior to partial or complete failure is not in the same order. The following Table 7 presents a summary of the data on movement of the bonded core sections.

Table 7

Chemical Grout System	Movement, inches	Rating
Epoxy-Bitumen	0.0535 (1)	1.000
Epoxy Resin	0.0575 (1)	1.075
Polyester Resin	~~0.144~~ (2)	0.269

(1) No complete separation at maximum load applied.

(2) Complete separation at maximum load.

These data indicate that the polyester resin although having greater compressive strength (See Figure 4) will accommodate only about 25 percent of the movement ability of either of the epoxy-based systems. This is considered an important factor in evaluating any chemical grout system to be used in the environment similar to that obtaining at the NORAD project.

21. The data are incomplete but another important performance characteristic in the compression loading of fractured rock bonded with chemical grouts is indicated by the ability of the epoxy resin bonded specimens to partially return to the original zero position for measuring movement. In Figure 1 the markings "X ⑬", "X ⑦", and "X ①" along the y-axis show the movement recovery 120 seconds after loading

release during the compression testing of the epoxy resin bonded cores. In contrast those fractured cores bonded with the polyester resin completely separated, therefore there was no recovery.

Shear Strength Analyses

Bonded Cores

22. It is interesting to examine the normal and shear stresses that occur along the bonded fracture of the cores tested in compression. Since the angle of fracture and the compressive stress at failure parallel to the axis of the core is known, the normal and shear stress on the fracture plane can be computed by means of the following formula:

Shear Stress

$$\tau_\theta = \frac{\gamma_x}{2} \text{ Sin } 2\,\theta$$

Normal Stress

$$\gamma_\theta = \gamma_x \text{ Cos}^2\,\theta$$

Where in,

γ_x = compressive stress at failure on a plane normal to the axis of the core

θ = the angle the fracture plane makes with the horizontal when the core is in an upright position

The following Table 8 summarizes these computations:

Table 8

Shear and Normal Stresses on Fracture Planes of Bonded Cores

Core No.	Fracture Angle, θ degrees	Compressive Strength, psi γ_x	Normal Stress, psi γ_θ	Shear Stress, psi τ_θ
		EPOXY RESIN		
13	20	8,220	7,258	2,642
14	20	7,960	7,029	2,558
7	45	2,960	1,480	1,480
8	35	4,315	2,896	2,027
1	60	2,450	613	1,061
2	55	2,830	931	1,330
		EPOXY-BITUMEN		
15	30	4,960	3,720	2,148
17	25	6,110	5,019	2,340
9	50	2,225	919	1,096
10	45	2,820	1,410	1,410
3	60	1,415	354	613
4	60	1,860	465	805
		POLYESTER RESIN		
16	20	8,155	7,201	2,621
18	25	13,480	11,072	5,163
11	45	6,170	3,085	3,085
5	55	6,730	2,214	3,162
6	60	4,325	1,081	1,873

23. The results of the computations shown in Table 8 are analyzed on Figure 6 by plotting the shear versus normal stress on the fracture plane for the three adhesive systems. The points for the epoxy resin and epoxy-bitumen are grouped together and are averaged by one straight line. The points for the polyester resin system have also been used to

define a straight line on Figure 6. The two straight lines (solid) on Figure 6 may be considered to represent failure envelopes for the polyester and epoxy systems, and may be compared to the Mohr envelopes obtained from the tensile and compressive strengths of the two adhesives. These values and the method of test are given in Part III of this report.

Epoxy Resin System

24. The shear strength of the epoxy resin system used can be examined by constructing a Mohr failure envelope using the compressive and tensile strengths at failure of the epoxy system. These values obtained from compressive and tensile specimens of the epoxy system at its ultimate strength were:

Tensile Strength - - - - - - - - 5,100 psi
Compressive Strength - - - - - - 7,500 psi

Figure 5 shows the values plotted and the circles for the Mohr envelope of rupture. It is also known that the seven-day strength of the epoxy cured under the conditions of the fractured core tests is about one-half its ultimate strength. This latter would be the strength of the epoxy in the bonded core specimens at the time of test. Since no tensile or compressive strength tests were made of the epoxy system at seven days, the use of one-half the ultimate strength for this value is an estimate. However, based on experience with these materials it is reasonably accurate. A plot similar to that for ultimate strength is shown for the seven-day strength on Figure 5, using the above estimate of one-half of the ultimate strength.

Polyester Resin

25. The tensile and compressive strength values given for the polyester resin by the producers representative at the 2nd Omaha Meeting were:

Tensile Strength - - - - - - - - 8,500 psi
Compressive Strength - - - - - - 20,000 psi

Applying the same procedures as for the epoxy resins system and unfractured rock cores, the Mohr envelope of rupture for the polyester resin can be defined by an angle of internal friction of 23.8 degrees and a cohesion value of 6,520 psi. This envelope is plotted on Figure 5.

Unfractured Rock

26. Using the tensile and compressive strengths of the unfractured rock, a Mohr envelope, similar to that for the epoxy, can be plotted on Figure 5. Values of tensile and compressive strength were selected from results of tests given in Tables 4 and 5 of this report. A conservative estimate of values based on the test results that are used for the plot on Figure 5 is:

Tensile Strength - - - - - - - - 1,070 psi
Compressive Strength - - - - - - 13,500 psi

When these values are plotted on Figure 5 the angle of internal friction indicated is 56.8 degrees and the value of cohesive strength indicated is 2,000 psi. The ultimate cohesive strength indicated for the epoxy is about 3,100 psi and at 7 days it is shown as 1,500 psi. These comparative cohesive strengths are significant only for the conditions of no confining pressures. However, for the purpose of assessing bond strengths in rock fractures grouted with the epoxy system they are in the right order of relative magnitude, since it is assumed that in an actual grouting operation the epoxy resin system will attain its ultimate strength.

Summary

27. The significance of the foregoing computations can be examined by plotting the Mohr envelopes for the epoxy resin systems and the polyester system on Figure 6 (dashed lines). Two envelopes are plotted for the epoxy resin system, one based on its ultimate strength and the other for its estimated seven day strength. This seven-day strength envelope for the epoxy resin system is plotted on the figure since it is compatible with the strength of the resin bonding the fractured cores. It will be noted that this line not only parallels the line for the fractured cores bonded with the epoxy systems, but it is also quite close to it (See Figure 6). This indicates that the shear strength developed in

the fractured cores tested in compression was quite close to the shear strength of the epoxy resin itself. In the case of the polyester resin system quite the opposite is indicated since the shear strength developed in the fractured cores was very much lower than that of the polyester resin itself (See Figure 6).

PART V: CONCLUSIONS

28. On the basis of the limited scope of the tests conducted and analysis of the data obtained, the following conclusions are justified:

a. The epoxy resin system employed in these tests has the desirable characteristics for the usage considered in that,

(1) The bond strengths and other properties are reasonably good.

(2) The system will accommodate appreciable movement before bond or material failure occurs.

(3) The shear strength of the epoxy system is compatible with that developed in the compression tests of the bonded cores.

(4) The effective volume shrinkage during curing is extremely low in comparison with that of the polyester resin and portland cement grout mixtures, and

(5) Variations in surface condition of the rock fracture surface do not appear to effect degree of bond obtained.

b. The polyester resin system used in these tests, although the strength properties are quite high, has some characteristics which may be undesirable for the usage considered since,

(1) The shear strength of the resin is appreciably higher than that developed in the compression tests of the bonded cores.

(2) Bond to dry surfaces of the rock is generally good but when rock is restrained for movement due to mass, over-all bond may be only fair to poor since,

(3) The effective volume shrinkage during curing is extremely high, and

(4) The system will accommodate only a relatively low order of movement before total bond or material failure occurs.

c. The epoxy-bitumen system used in these tests, primarily for informational purposes, showed that for future applications additional studies are warranted, since

(1) Bond to rock is excellent; but the strength of the

epoxy-bitumen, is generally only about 67 percent and 42 percent of the epoxy resin and polyester resin systems, respectively, and

(2) The epoxy-bitumen system will accommodate appreciable movement before bond or material failure occurs.

PART VI: RECOMMENDATIONS

29. The recommendations as a result of these studies in connection with the NORAD project and for future consideration are:

a. The epoxy resin system tested should be included in the test injections for rock-bonding at NORAD with polyester resins.

b. Additional studies of the potential epoxy-bitumen systems for rock-bonding should be made since these are equal in cost to the initially considered polyester systems and approximately one-half the cost of the epoxy resin system studied.

c. Future studies of chemical grout systems for rock-bonding should encompass both dry and wet (or moist) rock fracture surfaces.

d. Further studies should include triaxial tests of the unfractured rock and the chemical grout systems being considered.

e. Current specifications covering procedures for conventional grouting with portland cement mixtures are not suitable for grouting with chemical systems such as the polyester and epoxy resin systems; therefore, preparation of an applicable guide specification is needed.

Table 2

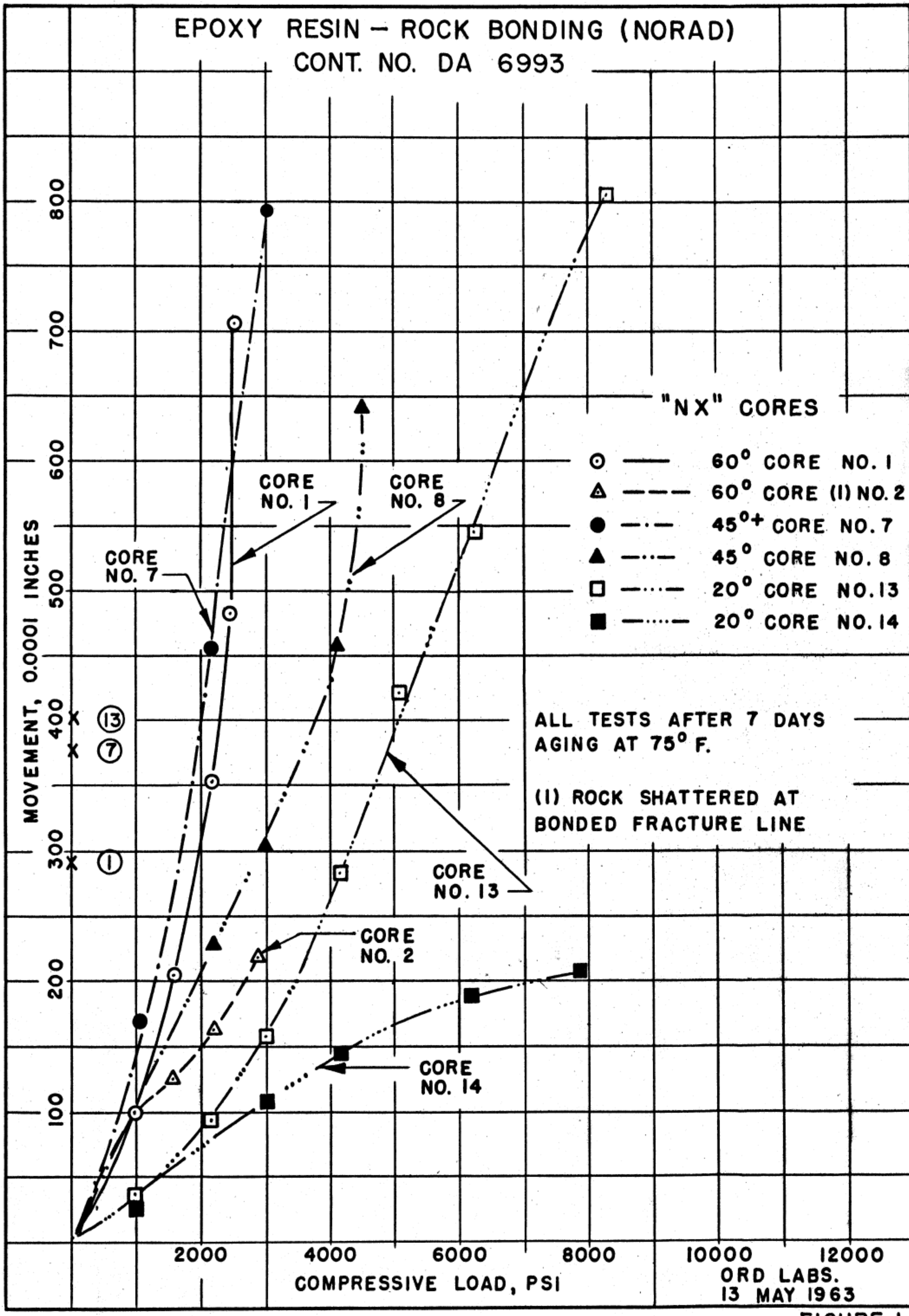
Log of NORAD NX Cores for Rock-Bonding Tests

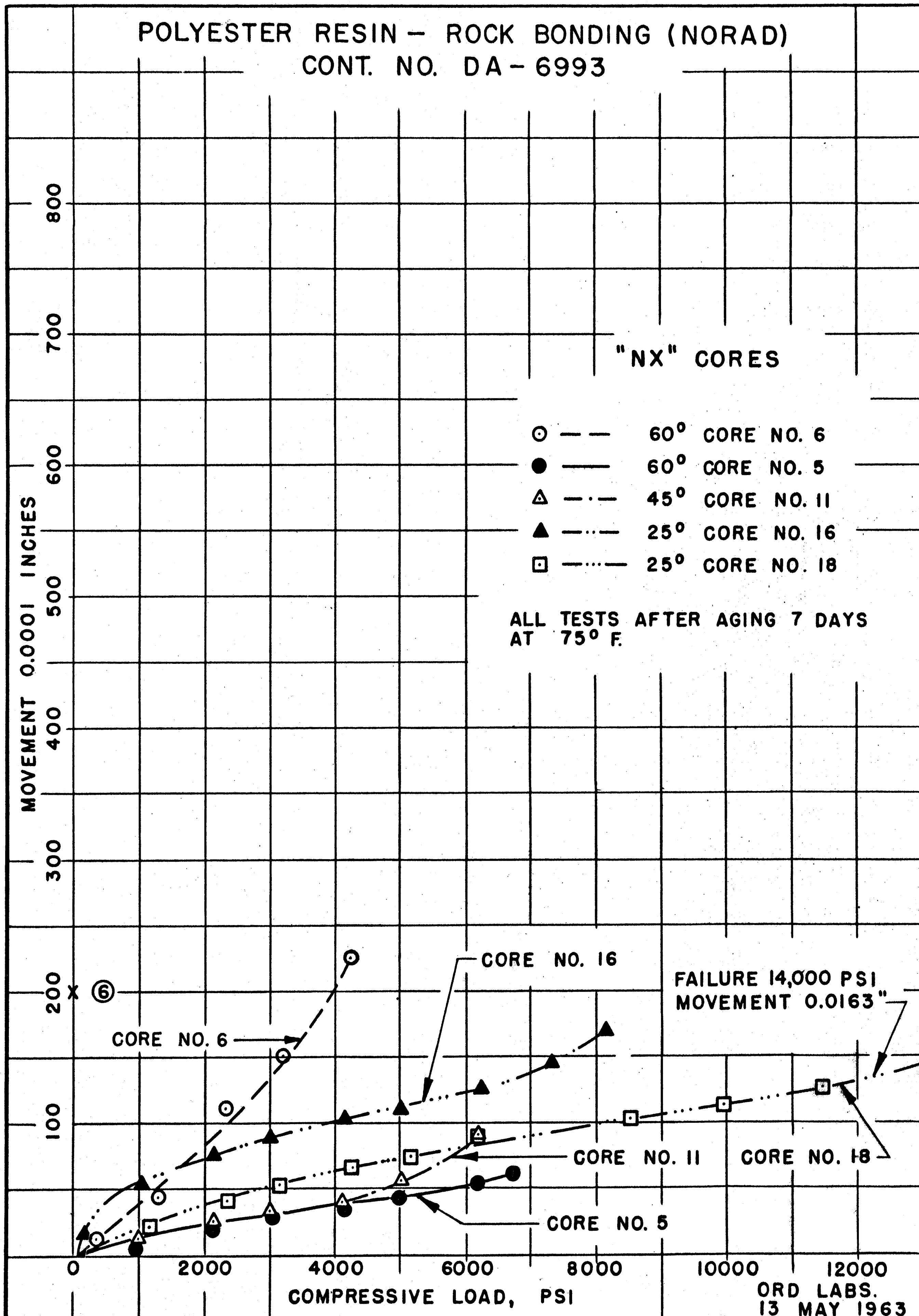
Core No.	Hole No.	Depth, feet	Fracture Angle, °	Description
1	A-11A	285	60	Fractured surface slightly weathered with calcite coating. Predominately quartz. Parallel unbroken joint 1/2" below fracture. Rock Class IV.
2	A-10	625	55	Fractured surface appears fresh but has thin finely crystalline calcite coating over 1/3 of surface. Also some drill cuttings principally on periphery areas intermixed with calcite crystals. Rock Class IV.
3	A-10	632	60	Fracture surface appears fresh but biotite grains show evidence of weathering. 50% of rock contact area missing. Rock Class IV.
4	A-11A	875	60	Fracture surface slightly weathered, has iron oxide staining with some (very slight) aleration of biotite to chlorite. Calcite healed fracture oblique to main fracture. Rock Class III to IV.
5	AN	2098.5	55	Fracture surface coated with magnetite, chlorite, and calcite. Rock is Class II to III.
6	A-6A	810	60	Fracture surface coated with magnetite and chlorite. Rock Class IV.
7	AN	559	45	Fracture surface coated with magnetite and minor amounts of calcite and iron staining. Rock Class II to III.
8	AN	650	35	Fracture surface coated with calcite and chlorite (predominant). Rock is Class IV with fine grained gneiss.
9	A-6A	874	50	Fracture surface coated with calcite and slightly weathered. Very minor amount of chlorite. Rock Class III.
10	A-10	1310	45	Fracture surface coated with calcite. Rock is Class III to IV.

Table 2 (Cont'd)

Log of NORAD NX Cores for Rock-Bonding Tests

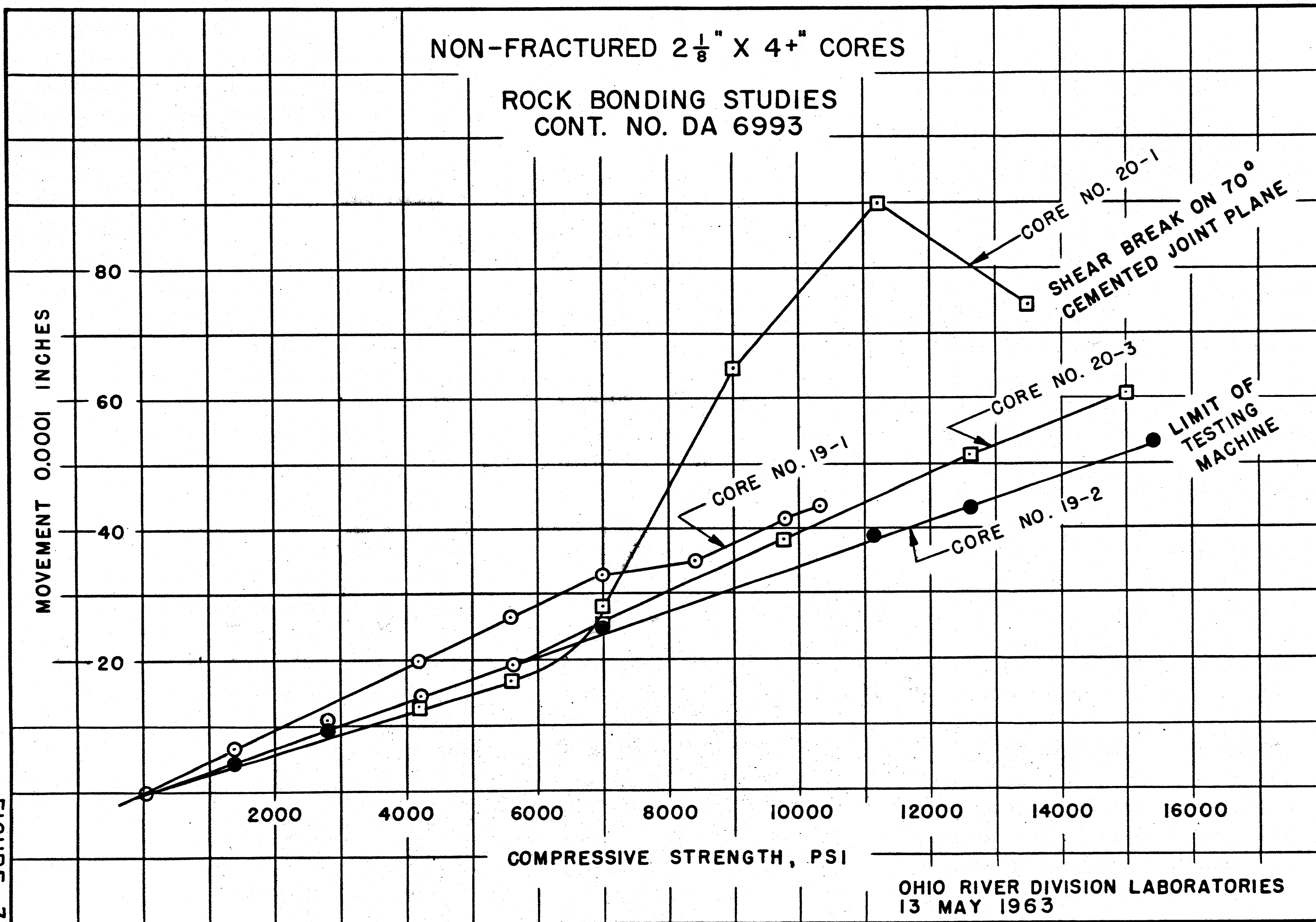
Core No.	Hole No.	Depth feet	Fracture Angle, °	Description
11	A-11A	1430	45	Fracture surface coated with calcite, magnetite, and biotite with the magnetite being predominant. Rock Class IV.
12	A-S	1595	50	Fracture surface coated with calcite and magnetite. Calcite predominant with slight weathering. Rock Class IV.
13	A-11A	1408	20	Fracture surface is fresh. Rock Class IV.
14	A-8	732	20	Fracture surface coated with magnetite and chlorite. Rock Class IV.
15	A-9	655	30	Fracture surface coated with calcite and chlorite (predominant). Rock Class IV.
16	A-9	886	20	Fracture surface 75% coated with calcite. Smooth break. Rock Class IV.
17	A-10	842	25	Fracture surface coated with chlorite, magnetite, and pyrolusite. Oil coating over 25% of surface. Rock Class III to IV.
18	A-6A	1103	25	Fracture surface coated with calcite (75% of surface). Fracture is relatively smooth surface. Rock Class III to IV
19	A-S	1996	None	No open fracture in sample. Rock Class II.
20	A-10	846 to 851	--	Machine fracture in sample. Rock Class IV.
21	--	--	--	Represents Class IV Rock.


EPOXY RESIN — ROCK BONDING (NORAD)
CONT. NO. DA 6993
"NX" CORES
60° CORE NO. 1
60° CORE (1) NO. 2
45°+ CORE NO. 7
45° CORE NO. 8
20° CORE NO. 13
20° CORE NO. 14
ALL TESTS AFTER 7 DAYS AGING AT 75° F.
(1) ROCK SHATTERED AT BONDED FRACTURE LINE
CORE NO. 1
CORE NO. 8
CORE NO. 7
CORE NO. 13
CORE NO. 2
CORE NO. 14
MOVEMENT, 0.0001 INCHES
COMPRESSIVE LOAD, PSI
100
200
300
400
500
600
700
800
2000
4000
6000
8000
10000
12000
13
7
1
ORD LABS.
13 MAY 1963
FIGURE 1



POLYESTER RESIN – ROCK BONDING (NORAD)
CONT. NO. DA-6993
"NX" CORES
60° CORE NO. 6
60° CORE NO. 5
45° CORE NO. 11
25° CORE NO. 16
25° CORE NO. 18
ALL TESTS AFTER AGING 7 DAYS AT 75° F.
MOVEMENT 0.0001 INCHES
800
700
600
500
400
300
200
100
X ⑥
CORE NO. 6
CORE NO. 16
FAILURE 14,000 PSI
MOVEMENT 0.0163"
CORE NO. 11
CORE NO. 18
CORE NO. 5
0
2000
4000
6000
8000
10000
12000
COMPRESSIVE LOAD, PSI
ORD LABS.
13 MAY 1963

FIGURE 2



NON-FRACTURED 2 1/8" X 4+" CORES
ROCK BONDING STUDIES
CONT. NO. DA 6993
CORE NO. 20-1
SHEAR BREAK ON 70° CEMENTED JOINT PLANE
CORE NO. 20-3
LIMIT OF TESTING MACHINE
CORE NO. 19-1
CORE NO. 19-2
MOVEMENT 0.0001 INCHES
80
60
40
20
2000
4000
6000
8000
10000
12000
14000
16000
COMPRESSIVE STRENGTH, PSI
OHIO RIVER DIVISION LABORATORIES
13 MAY 1963

FIGURE 3

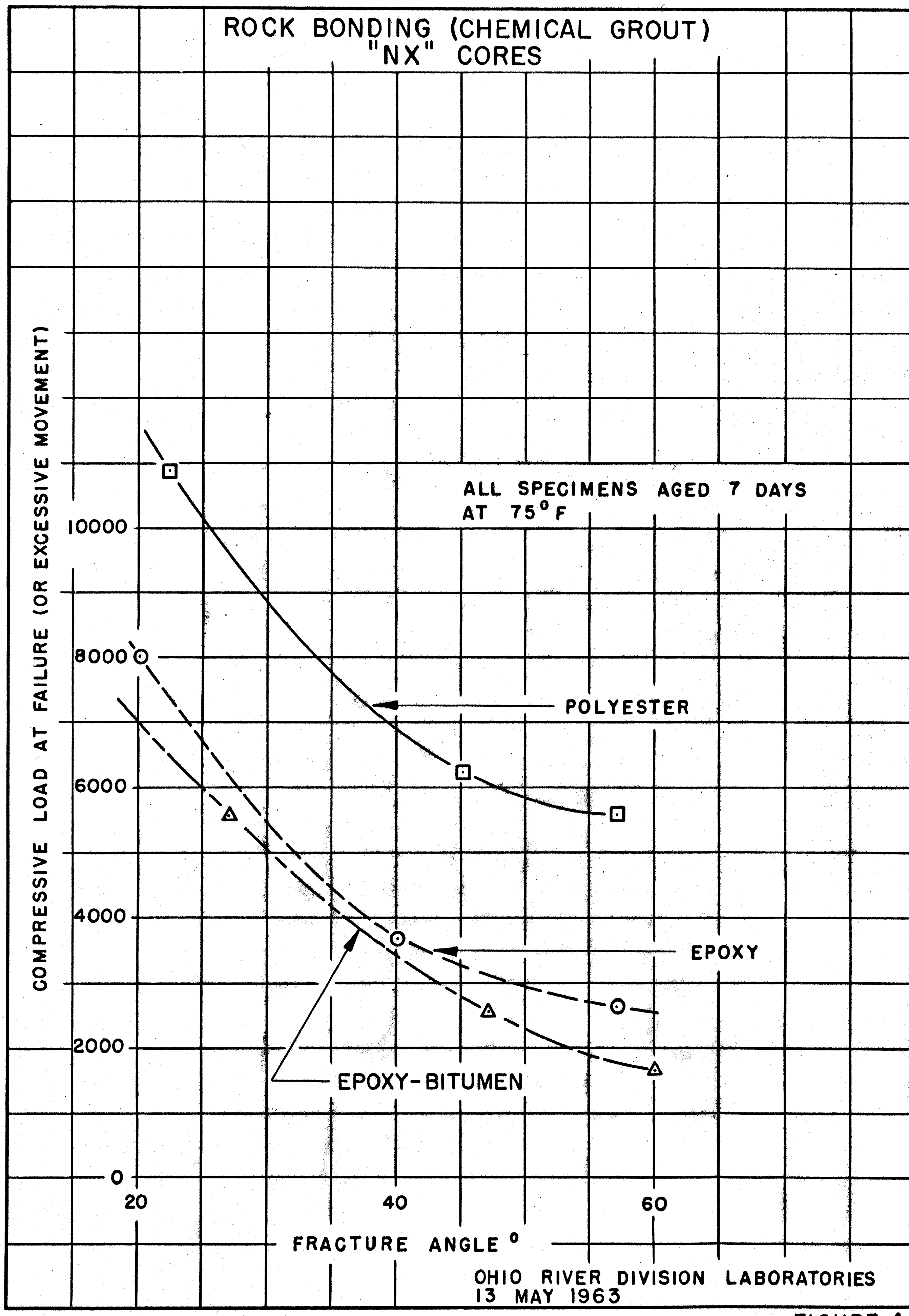

ROCK BONDING (CHEMICAL GROUT)
"NX" CORES
ALL SPECIMENS AGED 7 DAYS
AT 75° F
POLYESTER
EPOXY
EPOXY-BITUMEN
COMPRESSIVE LOAD AT FAILURE (OR EXCESSIVE MOVEMENT)
10000
8000
6000
4000
2000
0
20
40
60
FRACTURE ANGLE °
OHIO RIVER DIVISION LABORATORIES
13 MAY 1963

FIGURE 4

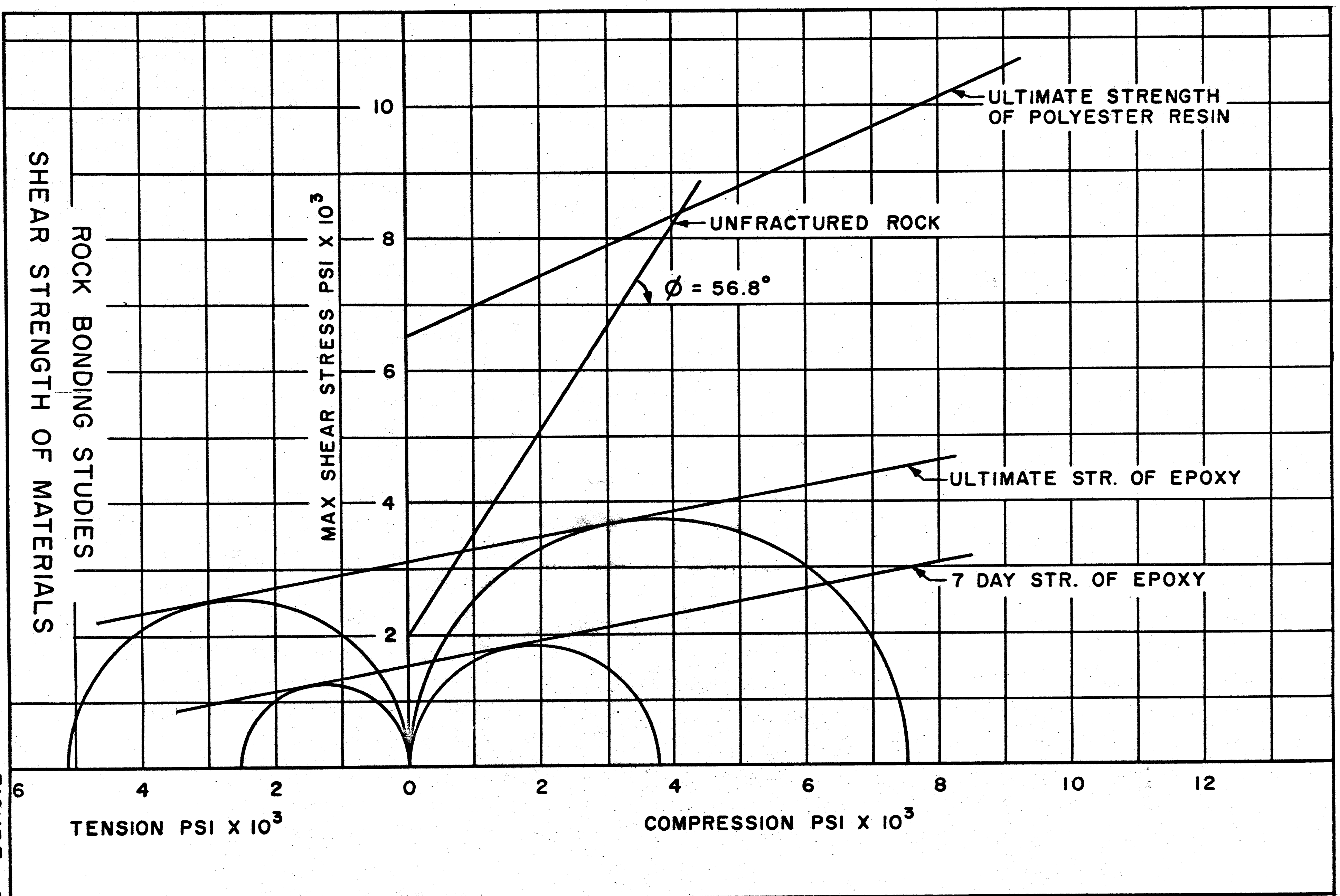
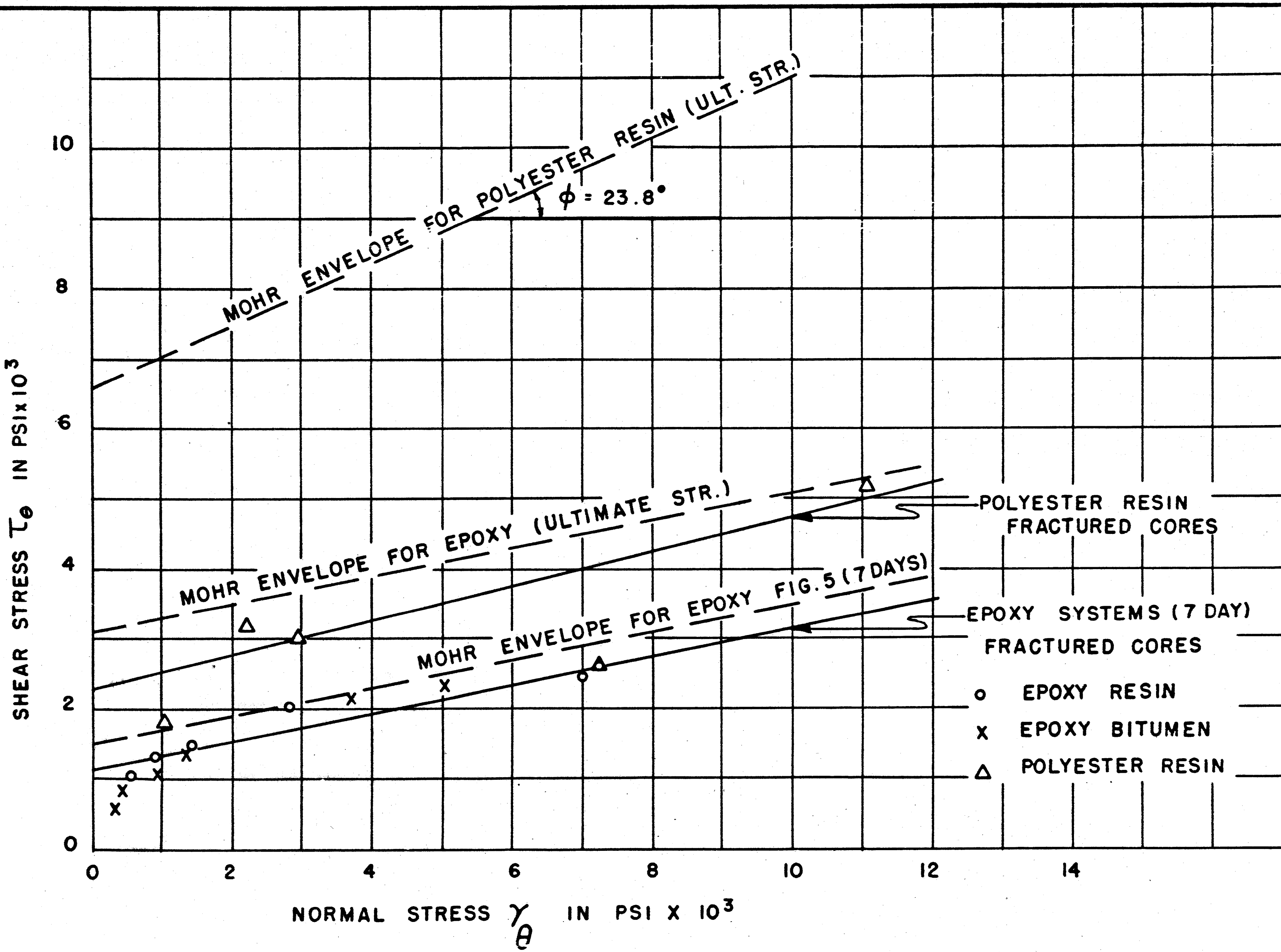

ROCK BONDING STUDIES
SHEAR STRENGTH OF MATERIALS
MAX SHEAR STRESS PSI X 10^3
10
8
6
4
2
ULTIMATE STRENGTH OF POLYESTER RESIN
UNFRACTURED ROCK
Ø = 56.8°
ULTIMATE STR. OF EPOXY
7 DAY STR. OF EPOXY
6
4
2
0
2
4
6
8
10
12
TENSION PSI X 10^3
COMPRESSION PSI X 10^3

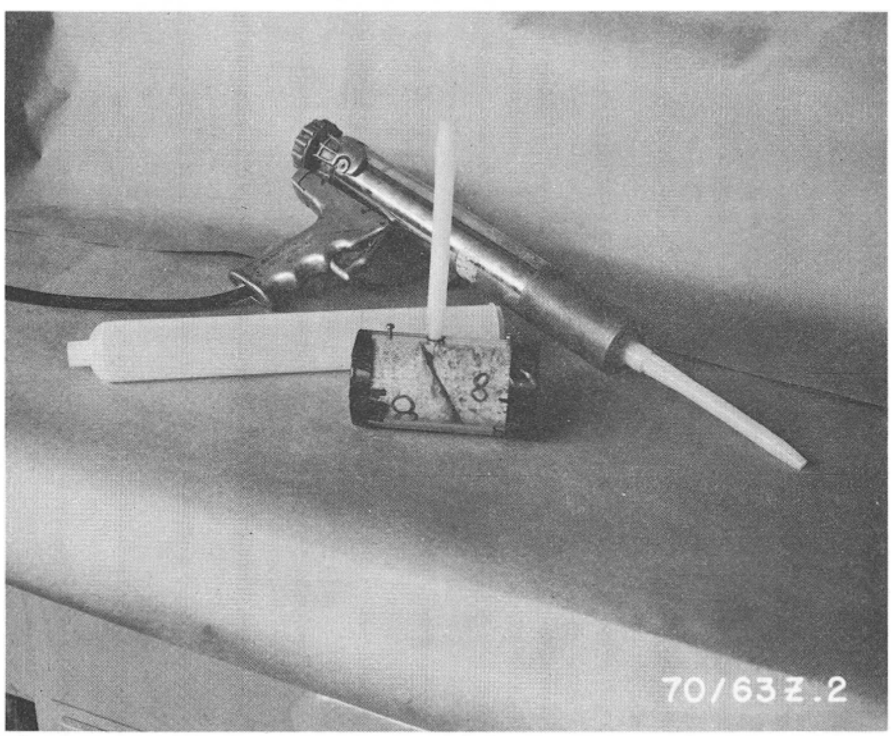
FIGURE 5



ROCK BONDING STUDIES
SHEAR STRENGTH ANALYSIS

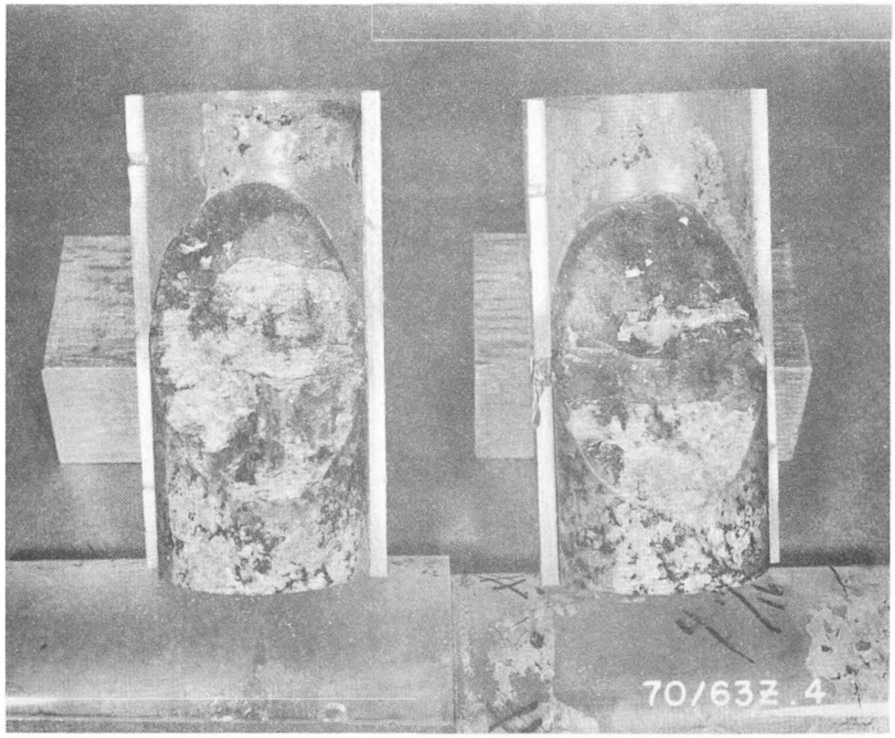
FIGURE 6

(a) Alignment and spacing of rock cores in lucite tubing, and showing end closure by neoprene tape to prevent leakage of grout.

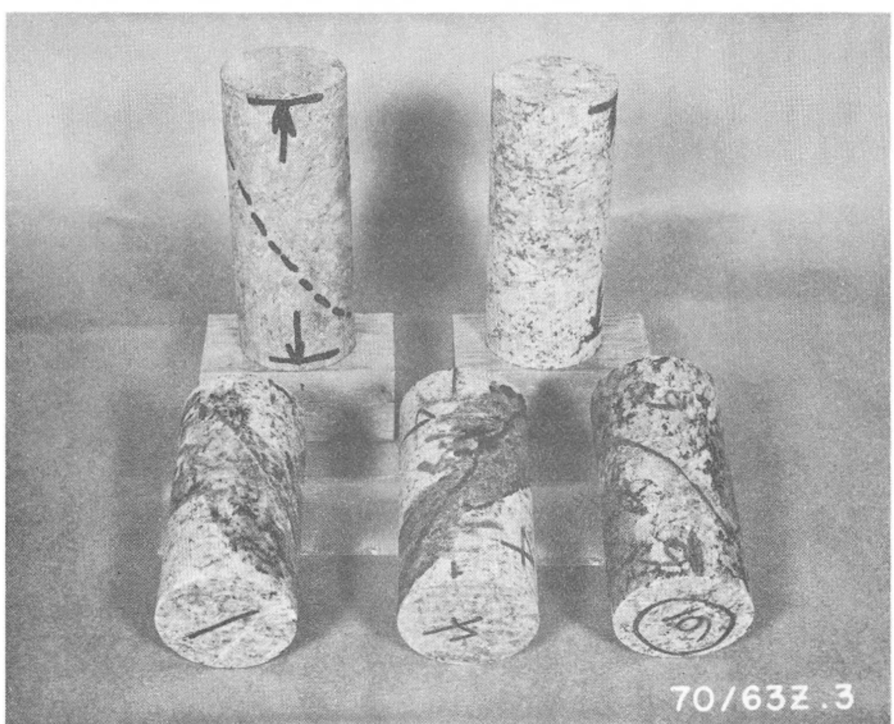


(b) Polyethylene nozzle used to transfer mixed grouts to separations in rock cores. Also shows screws used to hold rock core sections.

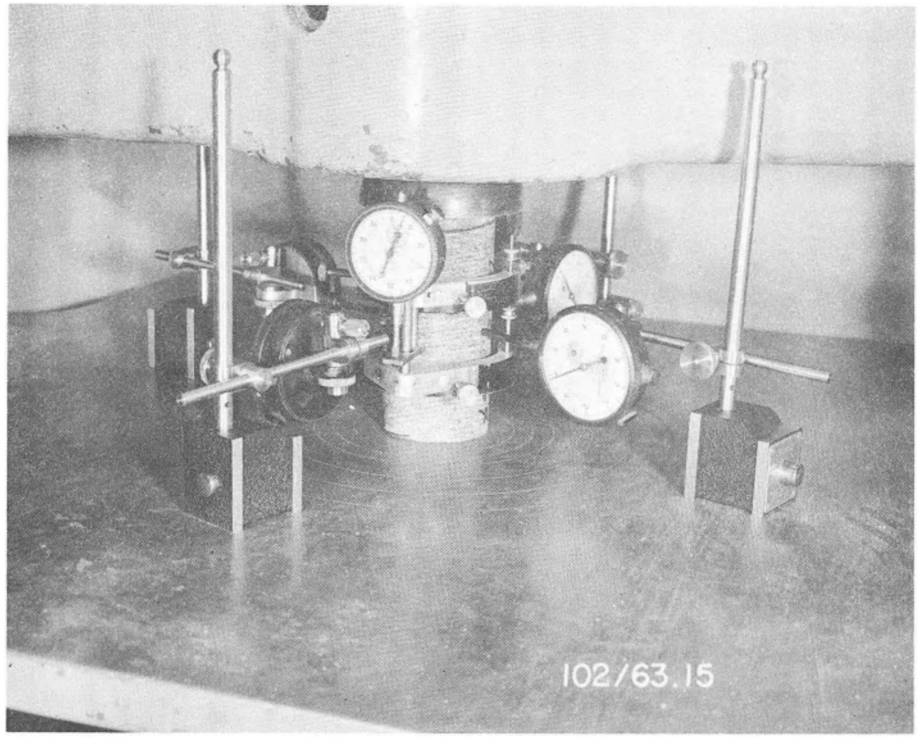
PLATE 1



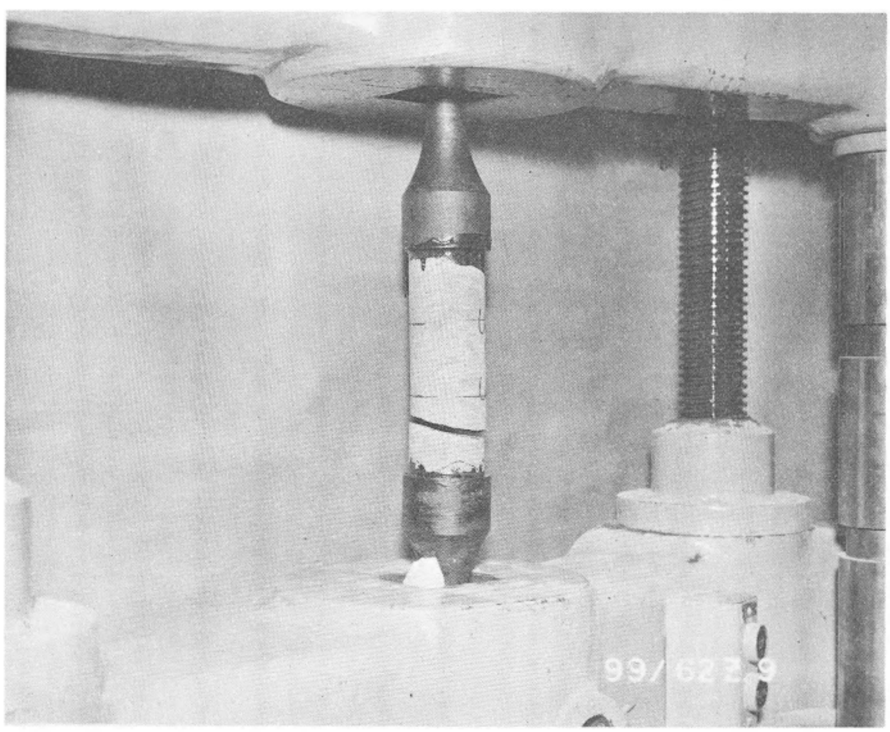
(a) Sawed halves of lucite tubing to remove bonded cores. Also shows Core No. 12 bonded with polyester resin which separated during sawing.



(b) Three chemical grout bonded cores (lower) and two non-fractured cores (upper).



(a) Movement gages attached to cores during compression testing.



(b) Rock core cemented in grips for tensile test.

APPENDIX A

MEMORANDUM

FILE SYMBOL: MRHGF

SUBJECT: Conference on Proposed Polyester and Epoxy Resin Grouting at NORAD

TO: Chief, Engrg Div
THRU: Chief, F&M Branch

FROM: H. B. Erickson
Sup Matl Engr

28 Feb 63

1. A conference was held at 8:30 AM on 27 February 1963 in conference room 6014B on the subject grouting. The personnel listed below attended this conference:

Name	Organization
B. U. Duvall	ORDL - Cincinnati
George L. Otterson	Construction Division
A. H. Bauman	Engineering Division
G. D. Haugse	Engineering Division
Robert C. Rector	Construction Division
L. S. Bray	Engineering Division
H. A. Sikso	Engineering Division
A. H. Burling	Engineering Division
J. M. Zeltinger	Engineering Division
C. J. Distefano	Engineering Division
H. B. Erickson	Engineering Division

2. Purpose. The purpose of this conference was to brief the Ohio River Division Laboratory representative on our present plans for the polyester resin grouting at NORAD and provide whatever assistance he desired for preparing their plan and cost estimate for the epoxy resin grouting which they may do.

3. The following is a summary of the conference:

a. Briefing. Mr. Duvall was briefed on our tentative plans for injection of the polyester resin in the pedestrian adit side of the A-2 Intersection. The possibility that this location may be injected with portland cement grout before the polyester resin grouting is scheduled was discussed; this may mean that some other site may have to be selected before the actual polyester resin grouting is done. The corner opposite B-3 and corner 3 of B-4 Intersections were also mentioned as possible locations for grout injection. The assistance we will receive in the grouting operation from the U. S. Bureau of Mines was discussed and also the proposed schedule of work (Starting drilling in late April and injection in early May to get 60° F. temperature minimum). The limited amount of funds to accomplish both types of grouting was also discussed.

b. Mr. Duvall made the following comments:

(1) Funds. The amount of funds available at present does not appear to be adequate for any actual injection at NORAD, but it may be enough to make some laboratory tests using epoxy resin to bond some core samples from NORAD and to make some other tests and a report. The report will indicate whether they believe it feasible or not feasible to actually do epoxy resin injection tests at NORAD.

(2) Previous Experience. They have bonded concrete but have not previously bonded rock with epoxy resin grout.

(3) Epoxy Resin Grout. Mr. Duvall indicated that the regular epoxy resin used by the Corps of Engineers would probably cost approximately $15.00 per gallon compared with about $5.00 per gallon for polyester resin. He indicated that many different compoundings of epoxy resin are available and that the addition of a filler might reduce the cost down to the polyester resin range. Mr. Duvall was not thoroughly familiar with the polyester resin we plan to use but was given a sample for use as he desires. He indicated that he felt that epoxy resin might give better grouting results for the following reasons:

(a) Epoxy should have somewhat greater strength than polyester.

(b) Epoxy can be compounded to bond to a wet surface and its wetting and bonding ability can also be adjusted.

(c) Epoxy resin is believed to have less normal shrinkage and develop less exothermic heat. This property might reduce the necessity for secondary grouting.

(d) The flexibilizer in epoxy may be desirable to tolerate small movements without breaking and its lower exothermic heat may cause lower residual internal stresses.

(4) Equipment. The Ohio River Division Laboratory does not have equipment suitable for injection of grout in the granite at NORAD but are of the opinion that they can rent or borrow suitable equipment. Mr. Duvall indicated he believed they could use a more simple injection method than the U. S. Bureau of Mines intends to use.

(5) Proposed Action.

(a) Mr. Duvall will advise the Director of the Laboratory of his findings on his return to the Laboratory.

(b) Mr. Duvall will advise us what rock samples he wants for laboratory bonding tests with epoxy resin. The Geology Section will secure the samples from NORAD. It is anticipated that old cores can be used for this testing work. This will make it possible to make a relatively quick check on the ability of epoxy resin to bond NORAD granite under different circumstances. Mr. Duvall also mentioned making a photoelastic analysis of the polyester resin to see what the residual stresses look like.

(c) If the bonding ability of epoxy resin is found favorable, they will set up a test program and furnish us an estimate of cost for a minimum program.

MRHGF 28 February 1963

SUBJECT: Conference on Proposed Polyester and Epoxy Resin Grouting at NORAD

4. An exit meeting was held at Mr. Hipp's office. The meeting was attended by Mr. K. S. Lane and L. B. Underwood of MRD, Mr. C. L. Hipp, H. A. Sikso, E. Soucek, A. H. Bauman and H. B. Erickson of the Engineering Division.

H. B. ERICKSON
Supervisory Materials Engineer

Copies furnished:

Colo Sprgs Area
Civ Des Br, (Bauman)
Mil Des Br, (Haugse)
Constr Div
ORDL
MRD

APPENDIX B

MEMORANDUM

FILE SYMBOL: MRHGF

SUBJECT: Conference on Polyester Resin Grouting NORAD - Contract DA-6993

TO: Chief, Engrg Div
THRU: Chief, F&M Branch

FROM: H. B. Erickson
Sup Matls Engr

15 Mar 63

1. A conference was held on the subject grouting in conference room 6014A on 13 March 1963 beginning at 9:30 AM and closing at 4:30 PM.

2. Personnel attending the conference are listed below:

Ray Mayewski	Producer B
Don McLean	Producer B
L. S. Bray	Omaha District
B. U. Duvall	Ohio River Division Lab
S. G. Spring	Omaha District
C. J. Distefano	Omaha District
G. D. Haugse	Omaha District
Oswin Keifer, Jr.	Omaha District
A. H. Burling	Omaha District
R. C. Rector	Omaha District
G. L. Otterson	Omaha District
A. H. Bauman	Omaha District (Afternoon Session)
H. B. Erickson	Omaha District

3. The following is a brief summary and items covered of the discussion during the conference:

a. Introduction. Mr. Bary monitored the conference. He introduced the Producer B representatives and explained that they would discuss the polyester resin grout which was proposed for use in test grouting in the A-2 Intersection. The Producer B representatives were in Omaha at our request. Mr. Bray stated that this office was concerned by the statement that during a conversation with Mr. Duvall, Mr. McLean had stated that Producer B now proposed to use a different material than had been tested in our laboratory. The Producer B representatives indicated polyester resin they propose for use will be the same as used in our test but will be modified some to produce a material with less shrinkage and equal in other qualities.

b. Cement Grouting. A specification is being prepared to cover portland cement grouting of the A-2 corner at NORAD. This is in accordance with instructions from MRD and a memo from the Chief of the Engineering Division to the F&M Branch. It is proposed to include drilling holes for the polyester resin grout injection, coring for evaluation and support facilities under the portland cement grouting specification. If laboratory tests now being made at the Ohio River Division Laboratory to bond samples of granite rock from NORAD with epoxy resin are favorable, it is proposed that several holes will also be injected with epoxy resin for evaluation.

c. Producer B Representative's Discussion of Polyester Resin. Mr. Don McLean provided the following information on their polyester resin:

(1) Service Record. Polyester resin has been injected in coal and metal mines for the last five years with what the company considers as very satisfactory results. The best way devised to evaluate the performance of polyester resin injections is said to be by continued observation and comparison with adjacent uninjected areas. As mining operations increase the static loading on columns and tunnel walls, the comparison in spalling and cracking is readily observable.

MRHGF 15 March 1963
SUBJECT: Conference on Polyester Resin Grouting NORAD - Contract DA-6993

(2) Properties. Various types of polyester resin are available and the properties of each can be varied by changing the components. The conditions of cure (mainly temperature and moisture) and other conditions of use should be specified when a polyester resin is ordered. A polyester resin can be made to cure at temperatures as low as 40° F. by the use of "promoters". This is believed to be lower than the minimum curing temperature of epoxy resin.

(3) Adhesion. Surface preparation is essential for high bond and a clean, firm surface is very desirable. Resins can be compounded to bond well to moist surfaces. Since the surface is all that is bonded, its condition determines the amount of bond. In drilled holes, roughness in the holes gives mechanical bond which helps to increase strength and the high internal strength of the polyester resin can be more fully utilized. Laboratory tests indicate pull tests using threaded bolts gave 8 1/2 tons for a 4-inch long bonded section. The material will adhere reasonably well to previously injected material (bonds to hardened sections). Thirteen different colors are available if color is needed for identification.

(4) Shrinkage. Shrinkage can run as high as 8%. Much of this shrinkage occurs during the last part of the hardening or curing. Modifiers are available to stop the cure when it reaches 85 to 90% completion, the use of modifiers reduces shrinkage. The 2.5% of shrinkage noted in the MRD Laboratory is fairly typical of the modified polyester resins as compared to around 1% for the epoxy resins. The Producer B has had no problem with shrinkage of their polyester resin used in filling cracks up to 1/8 inch in width or in bonding rods in drilled holes.

(5) Combining Grouts. Mr. McLean was quite doubtful of the results of injecting polyester resin after the area had been grouted with a cement grout. The cement grout would reduce the net bond across

an opening since it would form a layer on the rock to which the polyester would bond. The bond of cement to rock would become the controlling factor and the cement would have much less bond strength to the surface causing the combination to fail at the lower bond strength of cement grout. In addition, most voids would probably be filled with the cement grout making it difficult or impossible to get the stronger polyester resin into smaller voids. The conferees generally agreed that based on our laboratory tests and engineering judgment it would be best to inject the polyester resin first, evaluate it and if successful to consider continuing injection with the polyester resin instead of using portland cement grout. This will be kept in mind as the specifications are developed.

(6) Compounding Polyester Resin. In a fishing rod, a combination of 1% DDM and 99% resin are used. DDM is 60% methyl ethyl Ketone peroxide, (the accelerator). The DDM is diluted to 15% in the compounds we would use for grouting. The polyester resin is composed of a resin and a catalyst. The resin can consist of an alkyd, monomers (diluters), inhibitors, promoters and modifiers. In a polyester the first stage of hardening or curing is the gel stage, the second stage is complete hardening. The pot life or time from mixing to the gel stage and hardened stage can be adjusted by compounding. Adjusting curing time is an important asset of chemical grout since travel and consequent confinement of grout can be controlled over a wide range without changing shrinkage or other physical properties. At the International Nickel Mines in Canada, a polyester resin with a gel time of 20 minutes and a full cure of 2 to 3 hours was used. Bolts bonded with it were torqued to 300 foot pounds in 24 hours.

(7) Proposal for NORAD Grouting. Mr. Bray asked the Producer B representatives if their company would be interested in contracting to furnish materials, equipment and labor for injection of the

MRHGF 15 March 1963
SUBJECT: Conference on Polyester Resin Grouting NORAD - Contract DA-6993

polyester resin grout in drilled holes. Mr. McLean indicated that he was of the opinion that his company would be interested in contracting to do this work provided they did not have to drill the holes. The proposed data on this work as furnished below was given and a letter will be written providing this information and asking for a cost proposal on this work. The Bureau of Mines will also be informed of our proposed plan and probably will also be interested and available for performing the grout injection.

(a) Proposed Data.

(1.1) The injection of polyester resin will probably be accomplished in early May 1963.

(2.2) A three week advance notice should be made to insure availability of materials and delivery on time at the site.

(3.3) Polyester resin will be injected in between 5 and 14 holes and it is anticipated that between 100 and 400 gallons of polyester resin grout will be required. A quantity of 400 gallons will be made available on the site so no delay will be caused by a shortage of material. No bolts will be installed or grouted with polyester.

(4.4) Labor and materials for this work would be furnished by Producer B. A truck and the necessary utilities for grout injection will be required to be furnished by the Contractor who would also do the portland cement grouting.

(5.5) It is anticipated that the actual grout injection will take approximately 5 days and that it should be done before the portland cement grout is started.

(6.6) The polyester resin grout selected should be compounded for use in a moist hole with the rock at a temperature of 50 to 55° F. The gel time suggested was a minimum of 11 to 13 minutes to permit the material to penetrate cracks in the deeper holes.

(7.7) If the epoxy resin tests at the ORD Laboratory prove favorable, the injection of epoxy resin in drilled holes might be considered for inclusion along with the polyester resin injection program. This would have to be developed in detail later but it would require that equipment on the job be capable of injecting two materials in ratios of 1:15 and 1:0.6.

d. Mr. Duvall of ORD Laboratory mentioned that he has made some photo elastic analysis of polyester resin samples of No. 4151 and preliminary results indicate a first order stress fringe within two hours after placing and a second order fringe 20 hours after placing. The second order fringe compares to a stress of 550 psi versus 225 pounds at the same time for epoxy resin. No conclusions are available except that possibly the greater shrinkage of polyester causes the higher internal stress. Mr. Duvall indicated that the bonding tests with epoxy resin would be started almost immediately and that some results would be available within about two weeks.

4. Incorporating the polyester resin and epoxy resin grout injection program in the cement grouting contract will increase the amount of funds available for field work, laboratory testing, and evaluation of the chemical grouting and make it possible to stay within the authorized funds for rock bonding with chemical grout.

MRHGF 15 March 1963
SUBJECT: Conference on Polyester Resin Grouting NORAD - Contract DA-6993

5. Information gained from this conference is considered very beneficial since it provided much new information on polyester resin grout and its use.

H. B. ERICKSON
Supervisory Materials Engineer

Copies furnished:
U. S. Bur of Mines (R. H. Oitto)
Area Engr, Colo Spgs
Mil Des Br, Eng Div (Haugse)
Undergnd Str., Eng Div (Bauman)
Constr Div
F&M Br, Eng Div
Ohio River Div Lab (Duvall)

NOTE: In above text the company name was changed to "Producer B" by ORDL.

APPENDIX B

LOG OF INJECTION

1. EPOXY RESIN

8 May 1963

			Epoxy Added
a. Hole T-1 -- Start (1½"x18')	10:13	Air Pressure 25#	2 gal.
	10:18	"	2 gal.
	10:20	" 35#	
	10:26	" "	2 gal.
	10:29	Return water thru surface patches	
	10:38	Air Pressure 35#	2 gal.
	10:30	Gage P19 - .1735	
	10:41	Return by first bolt left of T1; thru grout vent tube same bolt; 3 small leaks thru surface crack cement seals	
	Pump Surges - 1 second		
	10:44	Air Pressure 35# Returns increased in number and intensity especially thru sealed surface cracks.	2 gal.
	10:49	- Pump Surges 2 seconds Stopped pumping; unhooked; Drive in Bullnose Plug.	

Estimated quantity pumped 8½ gal.
Estimated leakage loss 2 qts.
Ambient temperature 46°F.

Pumped 36 minutes   Total = 8½ Gallons Epoxy
Average Rate = 0.235 gpm

8 May 1963

			Epoxy Added
b. Hole T-2 -- Start (1½"x18')	10:51	Air Pressure 35# Pump surge ½+ sec.	
	10:53	Air Pressure 35#	2 gal.

8 May 1963 — Epoxy Added

b. Hole T-2 (Cont'd)

		Epoxy Added
10:53	Sealing off leak of T-1 either thru pignose or outside of sleeve	
10:58	"	2 gal.
11:03	"	2 gal.
11:06	Return water thru surface patches & around close anchor bolts	
11:09	Air Pressure 35#	2 gal.
11:09	Return continued w/slight increase around first anchor bolt below and slight left	
11:11	Return increasing-Epoxy noted	
11:14	Return water surface patch 3' below	
11:15	Pump surge 1 second	
11:18	Air Pressure 35#	2 gal.
11:18	Return epoxy anchor bolt below	
11:19	Return epoxy surface & bolts below and rt.	
11:20	Ambient temperature 48°	
11:29	Air Pressure 35#	2 gal.
11:30	Gage P19 - .1725	
11:37	Air Pressure 35#	2 gal.
11:37	Epoxy return thru surface patch 20" below and right @ 35° - plug with oakum	
11:40	New epoxy return 20" below and left @ 30° of T-1 hole also 7' left of T-2	
11:42	Stopped pumping. Pump surges 1 second. Plug hole.	

Pumped 51 Minutes   Total = 14 gallons
Average Rate = 0.275 gpm

8 May 1963			Epoxy Added
c. Hole A-8 -- Start (2½"x30')	11:46	Air Pressure 35# Pumping surge ½+ second	
	11:49	Air Pressure 35#	2 gal.
	11:57	"	2 gal.
	12:04	"	2 gal.
	12:05	Return water thru anchor bolt between T-3 & T-4	
	12:10	Air Pressure 35#	2 gal.
	12:15	"	2 gal.
	12:22	"	2 gal.
	12:22	Return epoxy thru hole 5' to right @ elev. 7032 - Plug w/oakum	
	12:25	Leak stopped w/plug Released Utah's truck service	
	12:29	Air Pressure 35#	2 gal.
	12:35	Above leak opened up - drove wood plug	
	12:37	Air Pressure 35# Pump surge 1 second	2 gal.
	12:39	Epoxy grout return T-3	
	12:44	Return anchor bolt between T-3 and T-4	
	12:47	Air Pressure 35#	2 gal.
	12:50	Small epoxy returns thru innumerable cracks and patches left in 10' vicinity	
	12:50	Leak of 12:22 increased; decided to shut down and permit setting - also improve plug Lunch	
	13:06	Start pump	
	13:13	Air Pressure 35#	2 gal.
	13:13	Small return T-4 - plugged	
	13:22	Air Pressure 35# Pump surge 1 second	2 gal.
	13:23	Stopped pumping to permit excess returns to set and improve plug on return of 12:22	
	13:35	Gage P19 - .1725	
	13:38	Start Pump Pump surge 1 second	

8 May 1963

c. Hole A-8 (Cont'd)

		Epoxy Added
13:45	Air Pressure 35#	2 gal.
13:45	Stopped pumping - permit set, improve plug	
13:57	Start pump	
14:07	Air Pressure 35#	2 gal.
14:08	Stopped pumping - afraid of losing plug of return 12:22	
14:10	Disconnect from A-8 Very small leak thru pig nose plug	

Pumped 128 minutes   Total = 26 gallons
Average Rate = 0.203 gpm

NOTES: Remaining material pumped w/air pressure 35# discharging into bucket just moves mixture thru end of nozzle.
Washed out equipment with Xylene.

2. POLYESTER RESIN

9 May 1963

a. Hole A-7 ($2\frac{1}{2}$"x30') -- Start 10:17

10:17	Line Pressure 60# Resin 90# Catalyst Pump Air Pressure 40#
10:31	1st return in surrounding 2' area thru surface fissures and patched cracks. Approx. 16 gal. injected.
10:37	Return water from grouted rock bolt 3' rt. up @ 45° when approx. 20 gal. had been injected.
10:38	Polyester appeared this leak including thru vent tube. Approx. 22 gal. injected. Gage P-19 read 0.172
10:40	Return water patched fissure below. Approx. 24 gal. injected.
10:45	Caught material leaking from bolt 10:37 to check gel time. (gel time - 10 minutes)
10:46	Gel material start seal leak

9 May 1963

a. Hole A-7 (Cont'd)

10:50 Approx. 32 gal. injected. Leakage around anchor bolt $2\frac{1}{2}$' right, 45' above.
11:00 Estimate 35 gal. pumped in 43 min. Leakage 12 to 15 inches above injector. Gage P-19 read 0.172
11:05 Return 10:37 down to drip.
11:07 Return 10:37 down slow drip, approx. 2 sec.
11:18 Pressure gauges indicate start of some back pressure about 1#. Disconnected and plugged hole.
11:18 Recap indicates approx. 44 gal. injected into this hole. Est. 4 gal. leaked out.

Pumped 61 minutes Total = 44 gallons
Average Rate = 0.723 gpm

9 May 1963

b. Hole B-7 -- Start ($2\frac{1}{2}$"x30')

11:21 Line Pressure - Resin 30#
Catalyst 90#
11:30 Completed 1st barrel (500# resin and 40# plus 1 qt. catalyst. Includes hole A-7) Approx. 8.6 gal. injected hole B-7.
11:32 Start 2nd barrel of resin same mixtures as before.
11:37 Return 1st leak 2' below and just right. Another 3' below approx. 16 gal. used from 2nd barrel in this hole. This return was 16" below the elev. of a top elev. leak while injecting into hole A-7.
11:37 Line Pressures Resin 40#
Catalyst 90#
11:45 Leakage at anchor bolt between B-8 and B-9, also leakage about 1' above injector. Approx. amount 36 gal. this hole.
11:50 Leakage 8' left and 1' below injector.

9 May 1963

b. Hole B-7 (Cont'd)

11:53 Leakage 4' rt. and 4' above injector.
11:57 Gage P-19 changed - 020 the wrong direction reading .210+ *
12:00 Noon Shut down ordered. Approx. 40 gal. injected this hole. Shut down due to movement and instructions of Mr. Ken Lord and Mr. Livingston. Material left in pump reservoirs.
13:00 Resin buckets returned to barrel.
14:00 No more grouting to be permitted this date. Start wash up equipment using Methol-Styrene Dial gage readings of P-19 are on Mr. Lord's report.

Pumped 36 minutes Total = 40 gallons
Average Rate = 1.11 gpm

10 May 1963

c. Hole T-8 -- Start (1½"x24')

13:55 No DMA (promotor) is added to mixture.

Air Pressure	60#
Resin	45#
Catalyst	21#
Stroke	35 sec.
Hole Temp.	46 degrees F.
Gage P-19	.129
Hole Depth	24 feet

14:04 Approx. 6½ gal. injected
14:06

Air Pressure	50#
Resin	40#
Catalyst	25#

14:08 8½ gal. injected
Leak 2' above slightly rt.
Leak 3' rt.
14:10 Leak 1' rt. 2' below (bolt)
Leak 4' down 1' left

Air Pressure	40#
Resin	30#
Catalyst	20#

14:11 Leak 3' down and 3½'
14:12 Return thru hole T-7 thru pignose plug
14:14 Injected 10½ gal.

10 May 1963

c. Hole T-8 (Cont'd)

14:15	Air Pressure	40#
	Resin	30#
	Catalyst	20#
14:18	Leak 8" above injector	
14:20	Air Pressure	40#
	Resin	30#
	Catalyst	13#
14:22	13 gal. injected	
14:26	Air Pressure	40#
	Resin	30#
	Catalyst	18#
14:28	Shut down pumping for Blast Corner B-2	
14:30	Start pumping	
14:31	Gage P-19 - .129+	
14:33	Injected 15½ gal.	
14:35	Air Pressure	40#
	Resin	30#
	Catalyst	18#
14:37	Leak 6" above grouted bolt 2' left of injector hole	
14:40	Injected 17 gal.	
14:45	Check of gel time = 26 min. @ 49°F. Tunnel temp.	
14:48	Injected 19 gal.	
14:52	Surface leaks not sealed but slowing down.	
14:54	Air Pressure	40#
	Resin	30#
	Catalyst	15#
14:55	Injected 21 gal. Average .35 gal/min. (very slow rate)	
15:00	Leak 1' up 1' left 3' up 1' right	
15:02	Injected 22½ gal.	
15:06	Leak 3' up	
15:09	Injected 24½ gal.	
15:10	Gage P-19 - .128+	
15:12	Air Pressure	40#
	Resin	30#
	Catalyst	15#
15:13	Leak grouted bolt 4' up 1' rt.	
15:17	Injected 26 gal.	
15:22	Start blending ½ & ½ premixed resin and DMA of 5/9/63 w/straight resin to improve gel time - next 14 gal.	

10 May 1963

c. Hole T-8 (Cont'd)

15:25 Leaks surface 5' up
Air 40# Resin 30# Catalyst 15#
15:30 Injected 29½ gal.
15:34 Leak @ grouted anchor bolt 4' up 4' rt. (5' above injector)
15:35 Injected 31½ gal.
Pump chatter: Air increased
Air 52#
Resin 40#
Catalyst 20#
15:40 Injected 33 gal.
15:43 Injected 34½ gal. P-19 gage read 0.128
15:45 Leak 6' left of injector
Leak 6' up 1' rt. of injector
15:48 Injected 36½ gal.
15:51 Injected 38 gal.
16:00 Air 50# Resin 40# Catalyst 20#
Stroke 30 sec. gentle w/o striking.
16:00 Leak 10' rt, 4' up from injector
16:05 Injected 40 gal.
16:08 Started adding 40 gr. DMA tested for 10 min. gel.
Injected 42 gal.
16:13 Injected 46 gal.
16:21 Injected 48 gal.
16:25 Gage P-19 - .127
16:28 Injected 50 gal.
16:28 1 bucket using 50 gr DMA (promoter)
16:30 Leak 8' up 1' left of injector
16:32 Injected 51½ gal.
16:33 Air 50# Resin 40# Catalyst 20#
Stroke 33 sec. Leakage at anchor bolt 1 ft. left and 8 ft. above injector.
16:40 Injected 53 gal.
16:40 Mix usi g 30 grams DMA
16:45 Injected 56 gal. - 2 new leaks above injector in back of the anchor bolt.
16:55 Injected 60 gal. - leakage 7½ ft. above and 1 ft. right of injector. Leakage around pipe in hole B-8
16:55 Pump chatter - raised air - 60#
Resin 40# Catalyst 24# -
Stroke 40 sec.
16:57 Leak 6' up 1' rt.
17:00 Gage P-19 - .126 - Injected 63½ gal.

c. Hole T-8 (Cont'd)

17:14 Injected 67 gal.
17:18 Leak thru bleed tube @ bolt 4' up 4' left of injector
17:20 Pump chatter to stall - increased air - 70# Resin 58#, Catalyst 35#, Stroke 40 sec.
17:24 Injected $72\frac{1}{2}$ gal. this hole
End 3rd barrel of total of 4 on job.
Computed barrel quantity 157.8 gal.
Est. quantities during progress 156.5 gal.
17:29 Start 4th barrel - Adding 30 gr. DMA
17:42 Stopped pumping this hole
Total injected 78 gal. in hole No. T-8
Demonstrated flow thru injector nozzle w/air 50# Resin 30#, Catalyst 5#
At this reading material just oozes off end of nozzle.

Pumped 227 minutes Total = 78 gallons
Average Rate = 0.343 gpm

d. Hole B-8 ($2\frac{1}{2}$"x30')

17:47 Pump refusal stroke travel 4". Hole evidently filled from behind and pignose plug held.
17:47 Disconnected nozzle

Pumped 0 minutes Total = 0 gallons
Average Rate = 0 gpm

10 May 1963

e. Hole T-6 ($1\frac{1}{2}$"x24')

17:54 Pump refusal - Stroke travel 4". Hole evidently previously filled.
17:54 Unhooked
17:58 Emptied reservoirs, wasted $1\frac{1}{2}$ gal. Proceeded to install sleeve down to $1\frac{1}{2}$" in hole B-10 for injection. Pumped $2\frac{1}{2}$ gal. on ground to check feed of catalyst. Start using 25 grams DMA.

Pumped 4 minutes Total = 0 gallons
Average Rate = 0 gpm

10 May 1963

f. Hole B-10 ($2\frac{1}{2}$"x30') -- Start 18:28

18:30 $3\frac{1}{2}$ gal. Air 80# Resin 62#
Catalyst 30# Stroke 20 sec.

10 May 1963

f. Hole B-10 (Cont'd)

18:34	Air 60# Resin 45# Catalyst 25# Stroke 27 Sec.
18:37	Injected 7 gal.
18:40	Gage P-19 - .124+
18:44	Injected 10½ gal.
18:45	Air 60# Resin 45# Catalyst 25# Stroke 27 Sec.
18:50	Water drip vent tube of grouted bolt 8' left. Injected 14 gal.
18:51	Resin appeared at vent tube. Plugged w/nail.
18:57	Injected 18 gal. Gage P-10 - 0.124
19:00	Air 60# Resin 45# Catalyst 30# Stroke 27 Sec.
19:05	Injected 21½ gal. Leak vent pipe grouted bolt 12' left of injector, plugged w/nail. Leak vent pipe grouted bolt 16' left of injector, Plugged with nail. Leakage at corner fracture 5 ft. below and 10 ft. right of injector.
19:08	Start using 45 gr. DMA
19:13	Injected 25 gal.
19:16	Start using 60 gr. DMA
19:17	Leak at crack & patch 4' rt. of injector.
19:19	Leak at crack & patch 4' down 1' rt.
19:20	Injected 28½ gal.
19:23	Leak @ cracks 5' & 6' rt. of injector. Leakage around anchor bolt 7' right of injector.
19:27	Injected 32 gal.
19:30	Leak at grouted rock bolt 5' rt. and 45° below injector.
19:35	Leak at crack 3' rt. and anchor bolt 3' right of injector. Resin 54#, Catalyst 32#, Air 68#
19:36	Injected 35½ gal.
19:37	Leak at rock anchor 3½' rt. of injector and 2½ ft. right of injector.
19:40	Air 68# Resin 54# Catalyst 32# Stroke 30 Sec.
19:42	Leak at crack to rt. moved up 2'.
19:44	Air 73# Injected 37 gal.
19:45	Gage P-19 - .123 P-15 - .193
19:50	Physically see polyester grout drip into hole B-11 but not filling hole. Leak at corner 10 ft. right of injector and 1 ft. up.

10 May 1963

f. Hole B-10 (Cont'd)

19:50 Stopped pumping B-10 and plug hole.
No more catalyst on job site.
Total injected 37 gal. (B-10)

Wash up using Methol-Styrene

Gage readings:

20:00 P-19 - .123
20:01 P-15 - .193+

Note: P-15 gage read 19:45 - .193
18:55 - .193

Pumped 82 minutes Total = 37 gallons
Average Rate = 0.45 gpm

APPENDIX C

STRATASCOPE LOG

Hole No. 1
Drilled Depth - 10'-1' = 9'
Date Drilled - 13 May 1963
Date Examined - 14 May 1963

Distance in from Collar (Always reads depth of hole.)	Width Description
11"	0.2" crack
1'-4"	0.05" crack & hairline crack
2'-3"	Series of cracks
	hairline crack
	0.05" "
	0.10" "
2'-10"	Series in 3/4" dist.
	0.025"
	0.025"
	0.15"
3'-1" to 4'-3"	0.05" fracture par. to hole
at 4'-3" fracture ends in	0.05" crack
4'-8" to 5'	Fracture parallel to hole varies from hairline to 0.1"
6'-3"	Hairline crack diag. across hole
6'-4"	* 2 cracks resin (epoxy) filled hairline to 0.01
6'-10"	* 0.8" diag. resin (epoxy) filled crack
8'-6"	0.05" crack
9'-0"	End of hole

*Bonding material also found in core during examination.

STRATASCOPE LOG

Hole No. 2
Drilled Depth - 20'-4" 10" left of T-4
Date Drilled - 15 May 1963
Date Examined - 15 & 16 May 1963

Depth	Width	Remarks
11" to 1'-3"	Badly shattered zone	*No grout showing
2'-2"	0.10 diagonal crack	*Open
2'-5"	0.05 crack	Open
2'-9"	0.025 crack	Open
3'-5"	0.025 crack	Resin filled (Epoxy)
3'-9"	Hairline crack	" " "
4'-2"	" "	Resin or calcite filled?
4'-6"	" "	*Resin filled (Epoxy)
4'-6½"	0.025" crack	Open
4'-9"	0.05 "	"
5'-0") 5'-3")	3 to 5" crack	*Resin filled (Epoxy)
6'-0"	0.2 diagonal crack	Open
7'-0"	0.50" crack	"
7'-3"	0.25" "	"
8'-10"	Hairline crack	Resin or calcite filled
9'-2"	0.1" crack	Open
9'-10"	0.025" crack parallel to hole	*Resin filled
10'-3"	Hairline crack diag.	*Resin filled
12'-0"	0.05" crack	Open
14'-6" to 15'-6'	Hairline crack parallel to hole	Resin filled
15'-9"	0.10" crack	Partially filled w/poly.
16'-8"	0.5" crack	Open
19'-5"	Hairline	Resin filled (brand?)
19'-9"	Bottom of hole	

*Bonding material also found in core during examination. At 10" to 15" the fluorescope indicated fluorescence in shattered rock also at 2'-2".

STRATASCOPE LOG

Hole No. 3
Drilled Depth - 30'
Date Drilled - 14 May 1963
Date Examined - 15 May 1963

Distance in from Collar	Width	Right Side of Hole Facing It
6"	0.10	*Resin filled (poly.) crack
7"+	0.075	* " " " "
10"	Hairline	* " " " "
1'	0.05	* " " " "
2'-2"	0.10	Cement filled crack
3'-4"	Hairline to 0.05	*Resin filled crack (poly.)
3'-9"	0.10	* " " " "
4'-2"	0.03+	* " " " "
5'-11"	0.05	Open crack
8'-1"	Diag. Hairline	Resin filled crack (poly.)
8'-8" to 9'-5"	Open crack diag. to hole 0.15	
9'-7"	0.05	Open crack
10'-9"	0.15	*Resin filled crack diag. to hole
12'-9"	0.05	*Resin filled crack (poly.)
13'-0"	Hairline	Resin or calcite filled
13'-5"	Hairline Diag.	Resin or calcite filled
14'-2"	3 Hairline	Open cracks
14'-5"	0.025"	Diagonal, open crack
15'-6"	0.20"	*Diagonal, resin filled crack (poly.)

*Bonding material also found in core during examination.

STRATASCOPE LOG

Hole No. 4
Drilled Depth - 5'-6" (drilled 6') 8" below and 4" right of T-3
Date Drilled - 15 May 1963 at noon
Date Examined - 16 May 1963

Depth

0 - 2'-8"	Numerous open fractures from hairlines to 0.2"
2'-10"	0.6" open rock
2'-10"	Solid rock to bottom of hole

Note: No bonding material found during examination of cores.

Hole No. 5
Drilled Depth - 10', 45° Down, 16" to right of T-1
Date Drilled - 15 May 1963 in afternoon
Date Examined - 16 May 1963

Depth

0 to 3'-10"	Numerous open cracks from hairline to 1/4" wide
4'-0"	1½" open fracture

Notes: Nothing below to 10' (solid rock)
No bonding material found during examination of cores.

STRATASCOPE LOG

Hole No. 6
Drilled Depth - 20'
Date Drilled - 16 May 1963
Date Examined - 16 May 1963

Depth		Width	Remarks
2'-10"		0.05"	Open
2'-11"		0.20"	Diag. Open
3'-3"		0.025"	Open
3'-8"		0.025"	Diag. Open
4'-5"		Hairline	No separation
4'-9"		"	Open
7'-7"		0.05"	*Pair poly. filled fractures
7'-8"		Hairline	*Poly. filled
7'-10"		0.2	Cement filled
7'-11"		0.2	" "
8'-4"		0.1	Open
9'-2"		0.15	"
10'-0"		0.05	Diag. Open
10'-3"		0.05	Open
13'-1"		0.05	Diag. Open
14'-7"		0.1	Diag. calcite filled
15'-0"	Pair	0.05	Open
15'-4"		0.05	Diag. Open
18'-4"		0.1	Parallel to hole and open
18'-6" to 18'-10"		Severely fractured zone	
18'-10"		End of hole	

*Bonding material also found in core during examination.

STRATASCOPE LOG

Hole No. 7
Drilled Depth - 8'
Date Drilled - 16 May 1963
Date Examined - 16 May 1963

Depth	Width	Remarks
2" to 11"	0.025	*Crack parallel to hole, partially filled with polyester
1'-10"	Hairline	*Poly. filled
2'-2"	0.50"	* " "
4'-2"	0.20	* " "
5'-4"	0.35	* " "
5'-7"	0.1	Open
5'-10"	0.1	Cement filled
6'-0"	0.5	Crushed zone, no resin
6'-3"	0.1	Diag. open
7'-8"	Bottomed in hole	

*Bonding material also found in core during examination.

STRATASCOPE LOG

Hole No. 8
Drilled Depth - 18'
Date Drilled - 16 May 1963
Date Examined - 16 May 1963

Depth	Width	Remarks
6"	0.45"	Open
7"	0.20"	Open
8"	0.50"	*Diag., partially resin filled
1'-1"	3.0"	*Poly. filled
2'-2"	0.025"	*Diag. poly. filled
2'-4"	0.10"	" open
2'-6"	0.05"	Open
2'-8" to 3'-0"	Numerous open fractures, hairline to 0.10	
3'-4"	0.20"	Open
3'-6"	0.50"	"
3'-8"	0.50"	"
4'-0		*3 diag. cracks, hairline to 0.15, epoxy filled
4'-2" to 4'-7"	0.05"	*Diag. poly. filled
5'-3"	0.10"	Diag. open
6'-5"	0.10"	" "
7'-2"	Hairline	*Resin filled (polyester)
7'-4"	0.15"	Diag. partly resin filled (poly.)
7'-6"	Hairline	Open
8'-2"	0.05"	Open
8'-10"	Pair of 0.05"	Fractures Open - 0.2" apart
9'-8"	0.05"	Parallel to hole and open
10'-0" to 10'-6"		Highly fractured zone, no resin
11'-11"	0.10"	Open
13'-0"	Hairline	Diag. open
13'-2"	"	" "
14'-0"	0.05"	" "
14'-5"	Hairline	" "
14'-6"	0.10"	" "
17'-5"		Bottomed in hole

*Bonding material also found in core during examination.