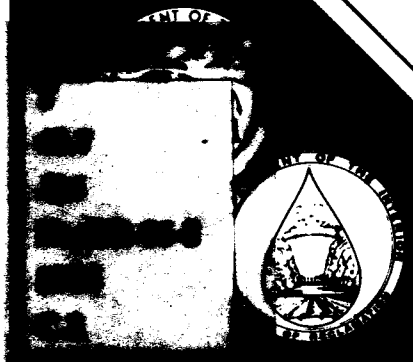
GR-86-2

ANALYSIS OF UTILIZATION OF GROUT AND GROUT CURTAINS — HOOVER DAM

February 1986
Engineering and Research Center



U.S. Department of the Interior
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16. ABSTRACT

The foundation grouting program at Hoover Dam was one of six large Bureau of Reclamation dams which was reviewed and analyzed. The purpose of this program was to analyze the use of foundation grouting in Bureau structures to determine the effectiveness of the grout over the service life of the dams to date. Special attention was given to preconstruction geological conditions and changed or unexpected geological conditions discovered during the grouting activities.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. *DESCRIPTORS--* grouting*/ cement grouts*/ dam foundations/ grout curtains/ grouting pressure/ grout take/ foundation grouting/ grout mixtures

b. *IDENTIFIERS--* Hoover Dam/ Arizona-Nevada/ LC Region

c. *COSATI Field/Group* 08H *COWRR:* 0808 *SRIM:*

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by

Claude A. Fetzer

Prepared under Contract No. 2-07-DV-00148

Concrete and Structural Branch
Division of Research and Laboratory Services
Engineering and Research Center
Denver, Colorado

February 1986

UNITED STATES DEPARTMENT OF THE INTERIOR ★ **BUREAU OF RECLAMATION**

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This report was published in the GR series from a copy of the report provided by the contractor, thus, the quality of photographs and figures may be less than usually acceptable.

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ANALYSIS OF UTILIZATION OF GROUT AND GROUT CURTAINS

HOOVER DAM

CONTENTS

CONTENTS--Continued

CONTENTS--Continued

LIST OF TABLES

LIST OF FIGURES

ANALYSIS OF UTILIZATION OF GROUT AND GROUT CURTAINS

HOOVER DAM

I. INTRODUCTION

1. General description. Hoover Dam and Power Plant are located on the Colorado River in Black Canyon on the Nevada-Arizona Stateline about 36 miles east of Las Vegas, Nevada, as shown on figure 1. The dam is an arch-gravity structure, which was designed to carry the water load by both gravity and arch action. It has a structural height of 726.4 feet above top of lowest rock in the foundation (El. 505.6 feet) and a hydraulic height of 592 feet. The dam has a crest (El. 1,232 feet) width of 45 feet and a crest length of 1,244 feet. The maximum width of the base is 660 ft. The plan and longitudinal section of the dam and appurtenant works are shown on figure 2.

The contract for construction of the dam by Six Companies, Inc. was approved on March 11, 1931. The first concrete in the dam foundation was placed on June 6, 1933, and concrete placement at the top of the dam was completed on May 29, 1935. The reservoir behind the dam, Lake Mead, had a capacity before sedimentation of 32,471,000 ac. ft. Impoundment of the reservoir commenced while the dam was being constructed and reached El. 895 feet on June 24, 1935, about one month after the final concrete was placed. By mid August 1935, the reservoir had reached El. 926 feet. The reservoir subsequently rose to El. 1,024 feet by September 1, 1937, to El. 1,173.9 feet in September, 1938, and to

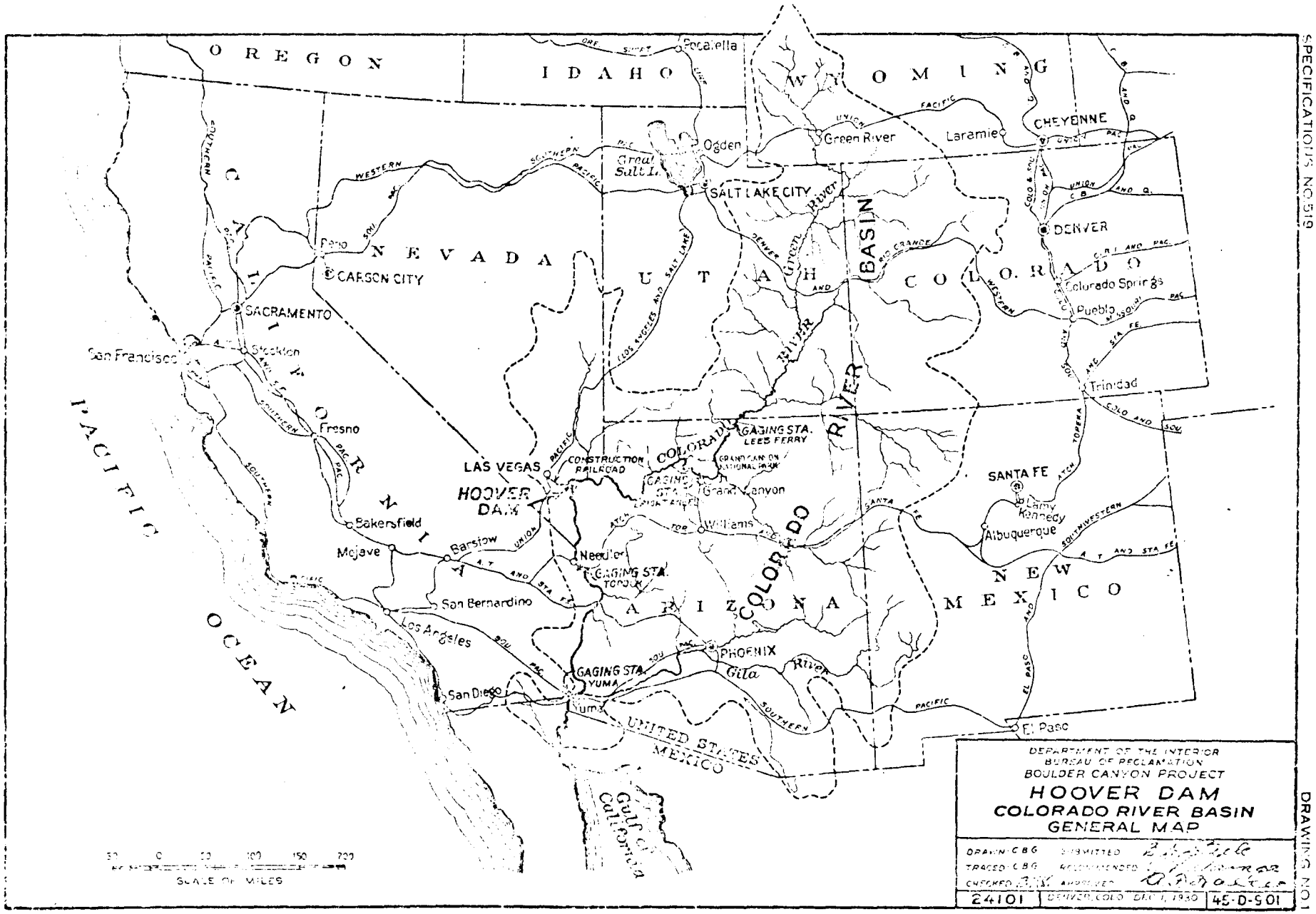
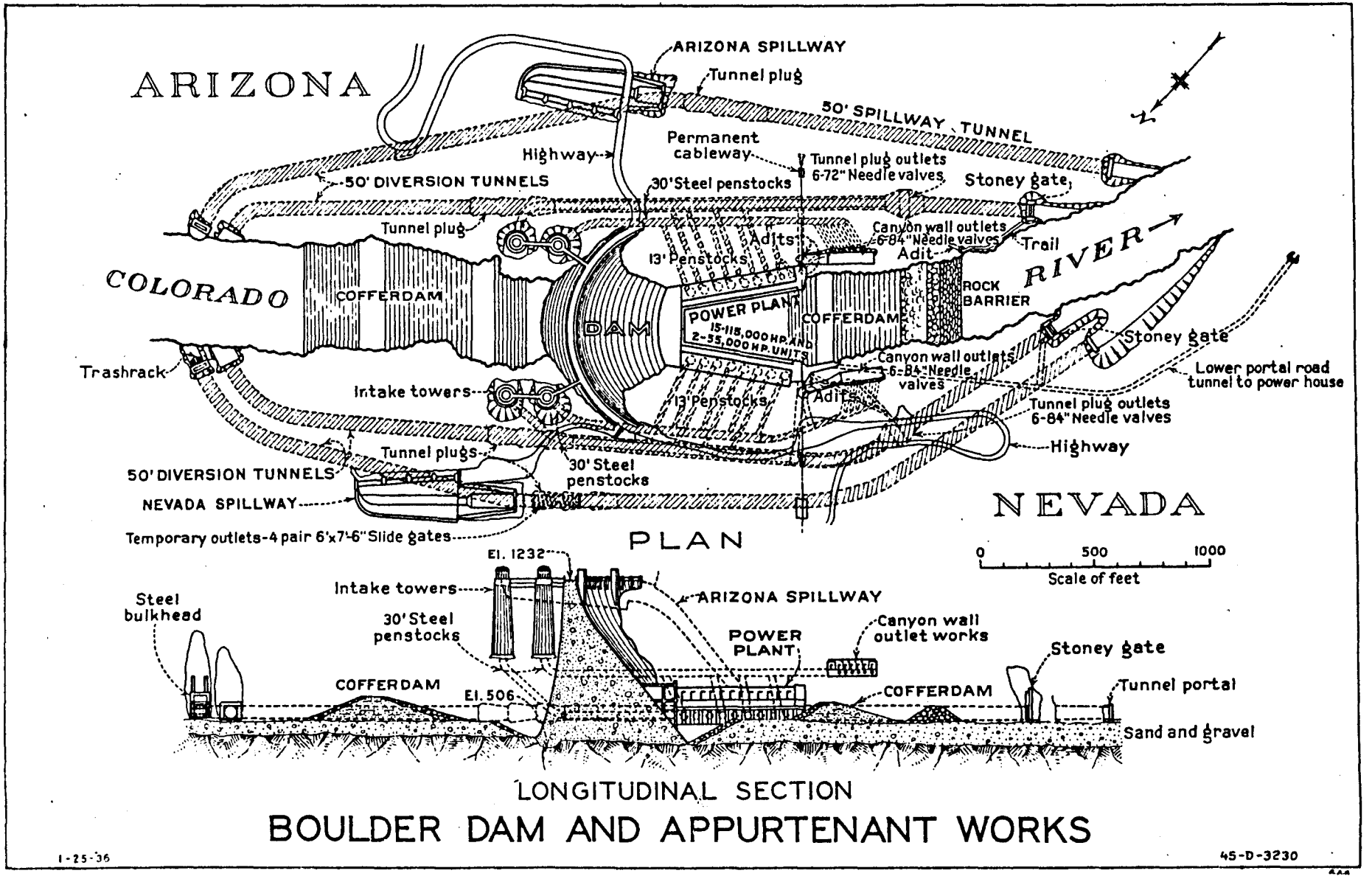

SPECIFICATIONS NO.519
DRAWING NO.1
OREGON
IDAHO
WYOMING
NEVADA
UTAH
COLORADO
CALIFORNIA
ARIZONA
NEW MEXICO
PACIFIC OCEAN
Gulf of California
UNITED STATES
MEXICO
COLORADO RIVER BASIN
HOOVER DAM
CONSTRUCTION RAILROAD
GAGING STA. LEES FERRY
GRAND CANYON NATIONAL PARK
GAGING STA. BRIGHT ANGEL
GAGING STA. TOPOCK
GAGING STA. YUMA
Green River
Gila River
Pocatello
Ogden
Great Salt L.
SALT LAKE CITY
Green River
Laramie
CHEYENNE
DENVER
Colorado Springs
Pueblo
Trinidad
Reno
CARSON CITY
SACRAMENTO
San Francisco
Stockton
Fresno
Bakersfield
Mojave
Barstow
San Bernardino
Los Angeles
San Diego
LAS VEGAS
Needles
Grand Canyon
Williams
PHOENIX
Yuma
SANTA FE
Lamy
Kennedy
Albuquerque
El Paso
OREGON SHORT LINE
UNION PACIFIC
SOUTHERN PACIFIC
WESTERN PACIFIC
DENVER AND RIO GRANDE WESTERN
LOS ANGELES AND SALT LAKE
C.B. AND Q.
C.R.I. AND PAC.
MISSOURI PAC.
COLO. AND SOU.
A.T. AND STA. FE
ATCH. TOPEKA AND SANTA FE
EL PASO AND SOUTHWESTERN
50 0 50 100 150 200
SCALE OF MILES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
BOULDER CANYON PROJECT
HOOVER DAM
COLORADO RIVER BASIN
GENERAL MAP
DRAWN: C.B.G.
SUBMITTED
TRACED: C.B.G.
RECOMMENDED
CHECKED: B.W.
APPROVED
24101
DENVER, COLO. DEC. 1, 1930
45-D-501

FIGURE 1



LONGITUDINAL SECTION

BOULDER DAM AND APPURTENANT WORKS

1-25-36

45-D-3230

FIGURE 2

El. 1,220.45 feet. on July 31, 1941 - the highest elevation shown in the available records.

During construction of the dam, the work area was protected by upstream and downstream earthen cofferdams. Diversion was achieved through two 50-foot-diameter diversion tunnels on the Arizona side and by two 50-foot-diameter diversion tunnels on the Nevada side. The outer tunnels on each side were later utilized as spillway tunnels. In the grouting report the outer tunnel on the Nevada side is labeled tunnel No. 1 and on the Arizona side, tunnel No. 4. The spillway structures were connected to the tunnels by steeply inclined lined tunnels. The spillway intake structure on each side consists of a concrete side channel with a crest elevation of 1,205.4 feet. Flow over each spillway is controlled by four 100-foot by 16-foot drum gates.

Normal release of the reservoir is achieved through the power plant, through the canyon wall outlet works, and through the inner diversion tunnel plug. Four intake towers were provided - two on either side of the canyon upstream from the dam. The upstream tower connects to the inner diversion tunnel and the downstream tower connects to a penstock header tunnel having a finished lined diameter of 37 feet which was reduced to 30 feet downstream of the power plant. The inner diversion tunnel on the Nevada side is labeled tunnel No. 2, and on the Arizona side, tunnel No. 3. The penstock tunnel on the Nevada side is labeled tunnel No. 5; and on the Arizona side, tunnel No. 6.

2. Grouting programs. The original grouting of the dam foundation was accomplished during the construction of the dam,

and major additional grouting was done during the period of 1938 to 1947, inclusive. Cement grouting was also used for the contraction joints in the dam, for the abutment slip joints, for the intake tower foundations, for contact grouting for all tunnels, for special grouting from the tunnels, and for the spillway foundations. This report is only concerned with the grouting for the dam foundation. However, it is recognized that the grouting of the appurtenant structures contributed to the overall seepage barrier at the site.

The names Hoover Dam and Boulder Dam are used interchangeably in this report.

II. GEOLOGY

3. Regional geology. Hoover Dam and Reservoir lie within two Physiographic Provinces, the Basin and Range Province on the west and the Colorado Plateau Province on the east. The dominant topographic feature of the area is the Black Mountain Range, a north-south range about 100 miles long traversing northwestern Arizona and extending about 10 miles into southeastern Nevada. The Colorado River cut Boulder Canyon through the westerly flanks of the Black Mountains to form Black Canyon. Hoover Dam is constructed in Black Canyon. The site is well suited for an arch dam, because the canyon is narrow with walls rising vertically about 450 feet before sloping gradually outward at the higher elevations. Figure 3, prepared by Ransome[1], shows the general topographic and geologic features of the region.

4. Site geology. The site-specific geology for Hoover Dam was described by the Bureau of Reclamation[2] in Bulletin 1, "Geological Investigations", and will only be summarized for the purpose of this report.

(a) Rock formations. Rock formations from Pre-cambrian through Pliocene are represented in the region, although nearly all the geologic formations in the vicinity of the damsite are considered to be of middle or early Tertiary age. The distribution of these units is shown on figure 4.

The rock formations exposed in the vicinity of the project are a series of complex lava flows and breccias with numerous intrusives; however, at the damsite there are only two principal formations. Rock in the lower elevations is a

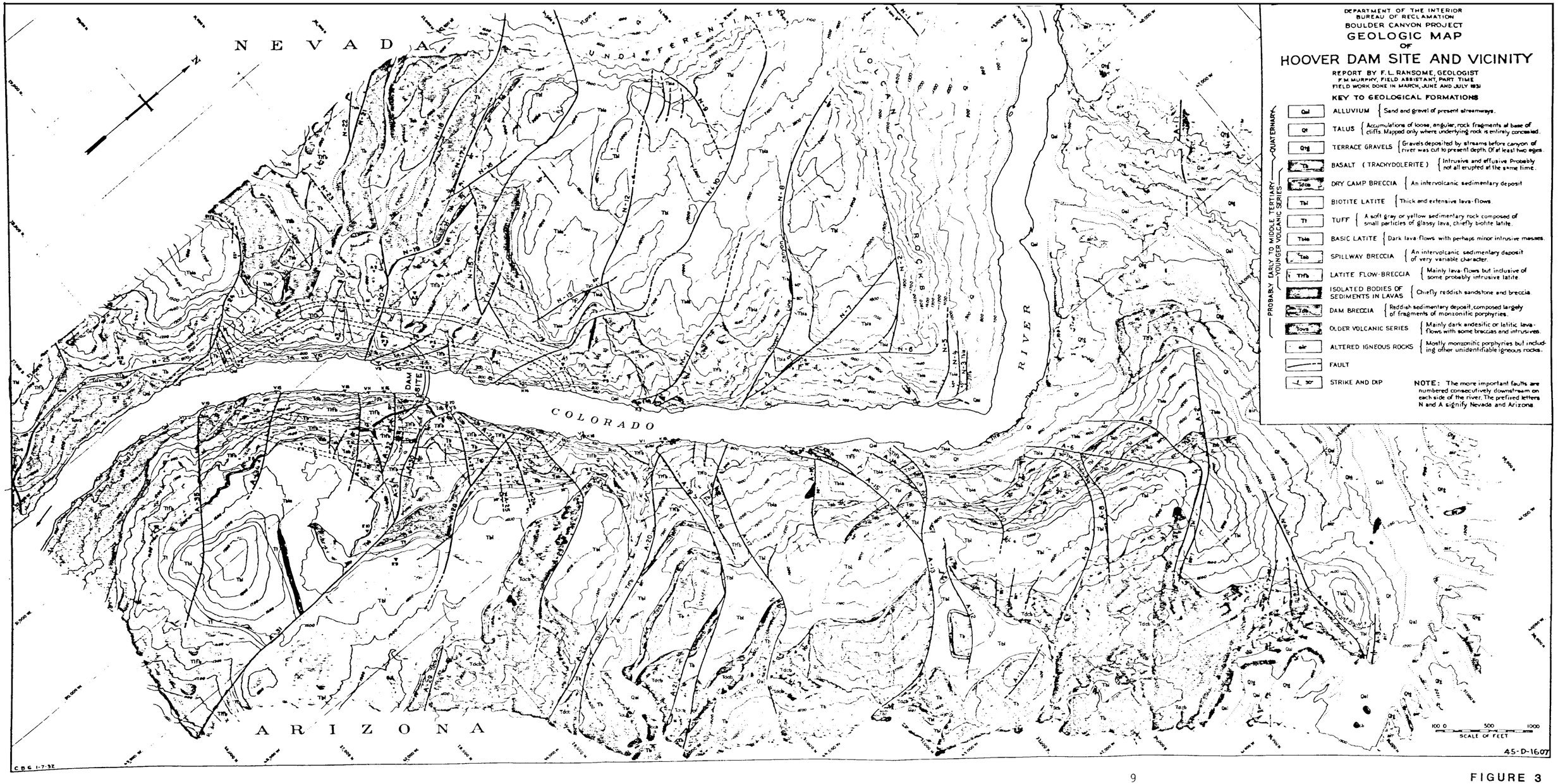
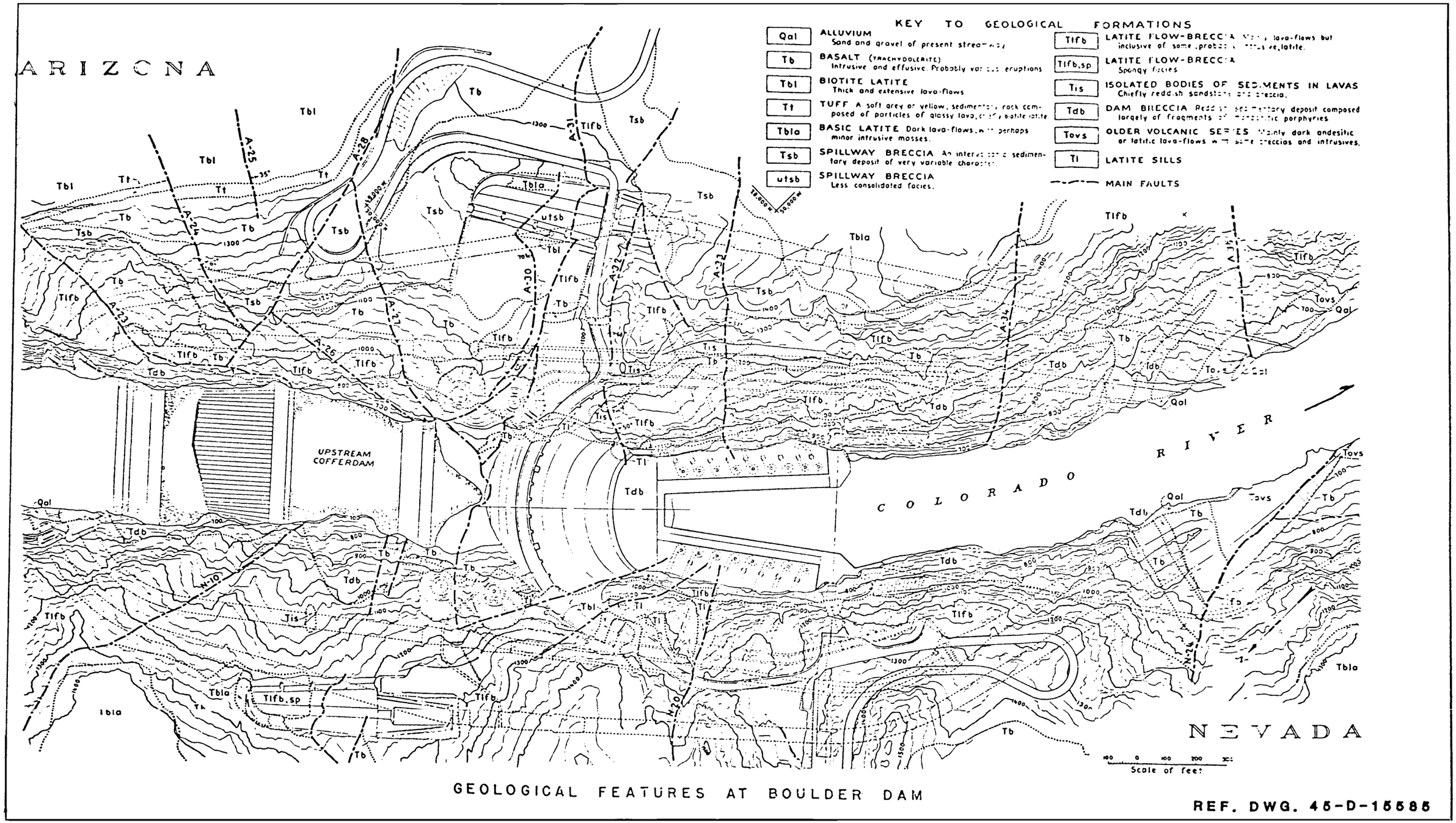

DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
BOULDER CANYON PROJECT
GEOLOGIC MAP
OF
HOOVER DAM SITE AND VICINITY
REPORT BY F. L. RANSOME, GEOLOGIST
F. M. MURPHY, FIELD ASSISTANT, PART TIME
FIELD WORK DONE IN MARCH, JUNE AND JULY 1931
KEY TO GEOLOGICAL FORMATIONS
QUATERNARY
Qal ALLUVIUM { Sand and gravel of present streamways.
Qt TALUS { Accumulations of loose, angular, rock fragments at base of cliffs. Mapped only where underlying rock is entirely concealed.
Qtg TERRACE GRAVELS { Gravels deposited by streams before canyon of river was cut to present depth. Of at least two ages.
PROBABLY EARLY TO MIDDLE TERTIARY
YOUNGER VOLCANIC SERIES
Tb BASALT (TRACHYDOLERITE) { Intrusive and effusive. Probably not all erupted at the same time.
Tdcb DRY CAMP BRECCIA { An intervolcanic sedimentary deposit
Tbl BIOTITE LATITE { Thick and extensive lava-flows.
Tt TUFF { A soft gray or yellow sedimentary rock composed of small particles of glassy lava, chiefly biotite latite.
Tbla BASIC LATITE { Dark lava-flows with perhaps minor intrusive masses.
Tsb SPILLWAY BRECCIA { An intervolcanic sedimentary deposit of very variable character.
Tlfb LATITE FLOW-BRECCIA { Mainly lava-flows but inclusive of some probably intrusive latite.
ISOLATED BODIES OF SEDIMENTS IN LAVAS { Chiefly reddish sandstone and breccia.
Tdb DAM BRECCIA { Reddish sedimentary deposit, composed largely of fragments of monzonitic porphyries.
Tovs OLDER VOLCANIC SERIES { Mainly dark andesitic or latitic lava-flows with some breccias and intrusives.
alr ALTERED IGNEOUS ROCKS { Mostly monzonitic porphyries but including other unidentifiable igneous rocks.
FAULT
30° STRIKE AND DIP
NOTE: The more important faults are numbered consecutively downstream on each side of the river. The prefixed letters N and A signify Nevada and Arizona.
NEVADA
ARIZONA
COLORADO
RIVER
UNDIFFERENTIATED
LOLCANIC
ROCK
CANYON
DAM SITE
SCALE OF FEET
100 0 500 1000
45-D-1607
CBG 1-7-32

FIGURE 3



GEOLOGICAL FEATURES AT BOULDER DAM

REF. DWG. 45-D-15585

FIGURE 4

sedimentary deposit and consists of a hard, durable, dark red cemented breccia referred to as "Dam Breccia", having an average compressive strength of 17,000 p.s.i. The upper part is a "Latite-flow Breccia", which is a light-colored reddish gray lava usually embedded with numerous small angular lava fragments and intruded with sill-like masses of latite and basalt dikes, figure 5. The "Latite-flow Breccia", has an average compressive strength of 11,000 p.s.i. The contact between the two breccias is irregular but is tight and almost indiscernible in places.

(b) Structure. At the damsite the formations strike northwesterly and dip upstream (northeasterly) at widely varying dip angles of 20° to 65°, dependent on the tilt of individual fault blocks. The Dam Breccia dips more steeply than the overlying Latite-flow Breccia.

There are numerous faults cutting across the canyon at approximately right angles as shown on Ransome's geology map, figure 3. In 1931, Ransome[1] commented that, "This map shows the area to be far more extensively faulted than was previously supposed, and had the geology map been available earlier to the opponents of Hoover Dam they would probably have made use of it as part of their propaganda". The prevailing strike of the faults is northwest and the prevailing dip southwest. The faults appear to be principally strike-slip faults and for the most part are tight and rehealed. The gorge at the damsite does not follow a fault zone.

(c) Hot springs. At several places within the walls of the inner gorge hot water flowed from crevices in the rock.

PLATE XIX

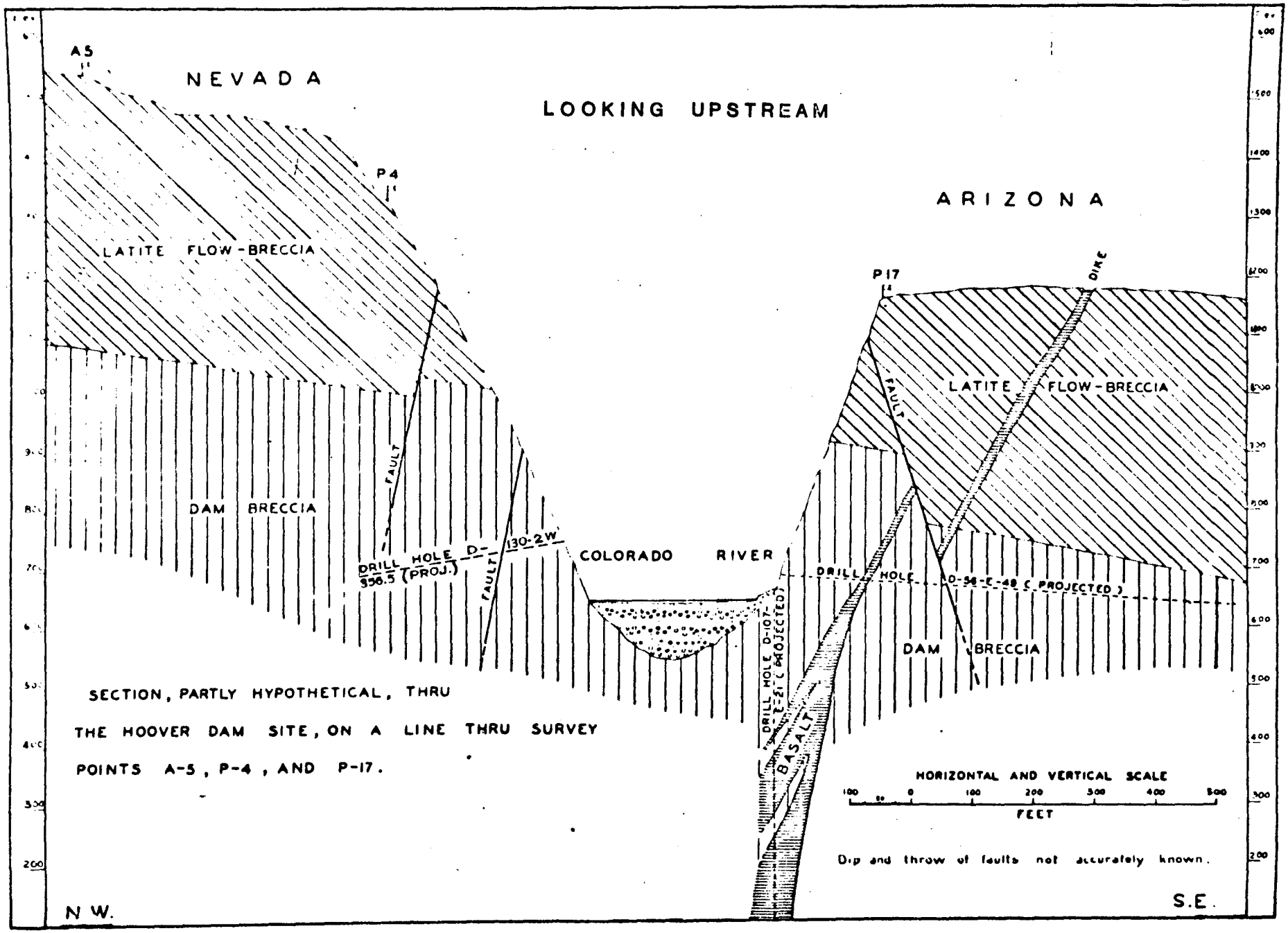


FIGURE 5

Temperatures of 88° to 99°F were found at two points just above the upstream toe of the dam whereas temperature of the river water was 62°F on the same date. The hot water is believed to have originated from deep seated sources and moved upward through fault systems under artesian head. Deep curtain grout holes encountered this water during the grouting process. Based on chemical analysis, the water was not harmful to the concrete, but was a cause of flash setting of the grout.

(d) Explorations. Prior to construction, there were approximately 41 exploratory borings drilled at the dam site as shown on figure 6. Thirty-nine of 41 borings were located in the bottom of Black Canyon. Because of the extreme difficulties involved in establishing drill hole "set-ups" on the steep slopes, only two horizontal borings were drilled into the abutments. All of the exploratory borings in the bottom of the canyon were vertical and were drilled through river fill. Twenty-seven of these borings penetrated bedrock to depths of 50 feet or less; however, one boring, DH-107-E-21, was drilled to a depth of 1,071 feet. Of the seven lines of borings, three lines were drilled within the dam foundation limits. Other lines of drill holes ran perpendicular to the abutments and were located upstream and downstream of the dam foundation.

The original field logs of the borings were not available for this study. Information on the deep hole and the two horizontal abutment holes is contained in a letter report, dated 14 February 1931, by F. L. Ransome[3] to Mr. R. F. Walter, Chief Engineer for the Bureau of Reclamation. In his report, Ransome

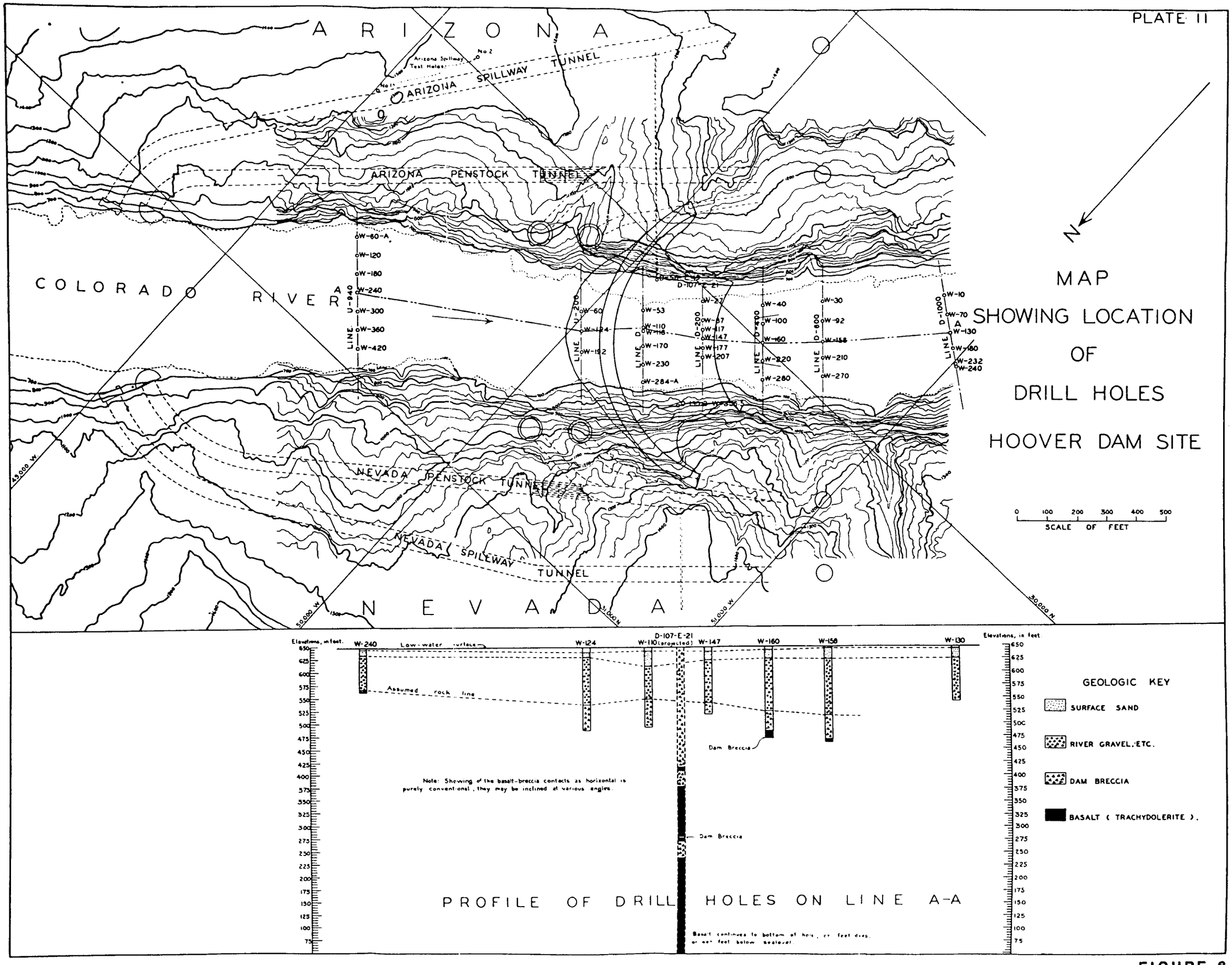


PLATE 11
ARIZONA
ARIZONA SPILLWAY TUNNEL
ARIZONA PENSTOCK TUNNEL
COLORADO RIVER
NEVADA PENSTOCK TUNNEL
NEVADA SPILLWAY TUNNEL
NEVADA
N
MAP SHOWING LOCATION OF DRILL HOLES HOOVER DAM SITE
SCALE OF FEET
PROFILE OF DRILL HOLES ON LINE A-A
Elevations, in feet.
Low-water surface
Assumed rock line
Dam Breccia
Note: Showing of the basalt-breccia contacts as horizontal is purely conventional, they may be inclined at various angles.
GEOLOGIC KEY
SURFACE SAND
RIVER GRAVEL, ETC.
DAM BRECCIA
BASALT (TRACHYDOLERITE).

FIGURE 6

discusses the following holes: horizontal hole No. 1 (D 56-E-49), drilled on the Arizona side at the dam site, to 752 feet; horizontal hole No. 2 (D 130-2W) located on the Nevada side at the dam site and drilled to 345 feet, where the bit was stuck in the hole; and vertical hole D-107-E-21 located on the Arizona side approximately 100 feet downstream from the dam axis and drilled to a depth of 1,071 feet.

Ransome describes the rock types encountered in respective reaches of each hole. In the deep vertical hole, D-107-E-21, basalt was encountered at a higher elevation than he had predicted, (based on earlier studies by Ransome when he made a boat trip down the river in 1922). Ransome regretted that neither he nor others were able to make a more detailed geologic study of the area prior to construction and wrote:

> "It may be remarked, in this connection, that the construction of the highest dam in the world might well have been preceded by far more detailed geological work than has been done in Black Canyon. The only geological information available has been that embodied in my report of 1925, which was obviously of preliminary character, and in a reconnaissance report on a proposed spillway by H. A. C. Jenison, made later in the same year. Had the canyon been adequately mapped, topographically and geologically, on a scale of from 100 feet to 200 feet to the inch, many of the questions which are now arising as to drill holes, tunnels and spillways could be more satisfactorily answered. The cost of such detailed study would have been a very small item in a project of such magnitude".
>
> "The foregoing remarks, fortunately, do not imply any doubt as to the satisfactory character of the dam site. They merely indicate that final commitment to so stupendous a project without thorough and detailed geological investigation was fraught with danger and that many questions which must from time to time come up, answers to which, if not vital, are at least desirable, can not be satisfactorily answered without such detailed study".

Ransome's comments describing the cores from the drill holes do not mention fractures, drill water losses or descriptions of other rock defects that might provide clues or other information useful in assessing the grouting and drainage requirements for the project. One such clue was hinted at where Ransome wrote, "In horizontal hole No. 1, between 403 and 426 feet, the core is reported to have been somewhat fragmentary and some relatively soft, red material was washed out of the hole". The drill logs of these holes were not available for this study; therefore, it was not possible to determine what if any significance or relationship the described condition might have had on the seepage that developed in this area, or whether this condition was encountered during any of the grouting operations. These borings are shown on the profile on figure 5. Figures 5 and 6 are from Ransome's[1] report.

III. FOUNDATION TREATMENT

5. Abutments. The explorations showed that the rock in the canyon walls was sound within five feet or less from the surface. While only five feet of surface rock needed to be removed to secure a satisfactory foundation, in most instances construction requirements, such as working benches for men and equipment, made it necessary to remove more than this amount. In a limited area near the top of the Arizona abutment, the latite-flow breccia was decomposed to a depth of two feet. As a result, it was necessary to remove the rock to a depth of about six feet beyond the depth assumed in the original design.

After the abutments were cleaned and excavated they were examined by Berkey[4], whose report stated:

> "Every foot of the bearing surface could be observed and reviewed which left nothing to conjecture. The foundation rock is sound and reasonably uniform and unusually free from objectionable or large weaknesses. Such fractures, joints and soft spots that do exist, are distributed in heterogeneous manner so that they do not establish continuous lines of weakness and consequently can be easily covered or bridged over. Even the major joints and slips are for the most part tight and many of them are rehealed. Such as are still open can be grouted without unusual difficulty. All of these features are being mapped and recorded for possible future reference by the staff geologist, Mr. Nickell."

6. Rock floor. The rock floor was exposed after removal of about 120 feet of river fill consisting of well stratified, densely compacted layers of sand, gravel, cobbles and boulders. An inner gorge was encountered that formed a narrow tortuous channel along centerline and reached depths of 75 to 80 feet below the rock benches on either side. The walls of the inner gorge

were deeply pitted and fluted and markedly uneven. During construction the walls of the inner gorge were beveled back to a slope of about 45° to avoid stress concentrations. Along the heel or upstream portion of the base of the dam, the rock was excavated to about 30 feet below the original gorge floor elevation, for placement of an upstream cutoff or foundation key as shown on figures 7 and 8.

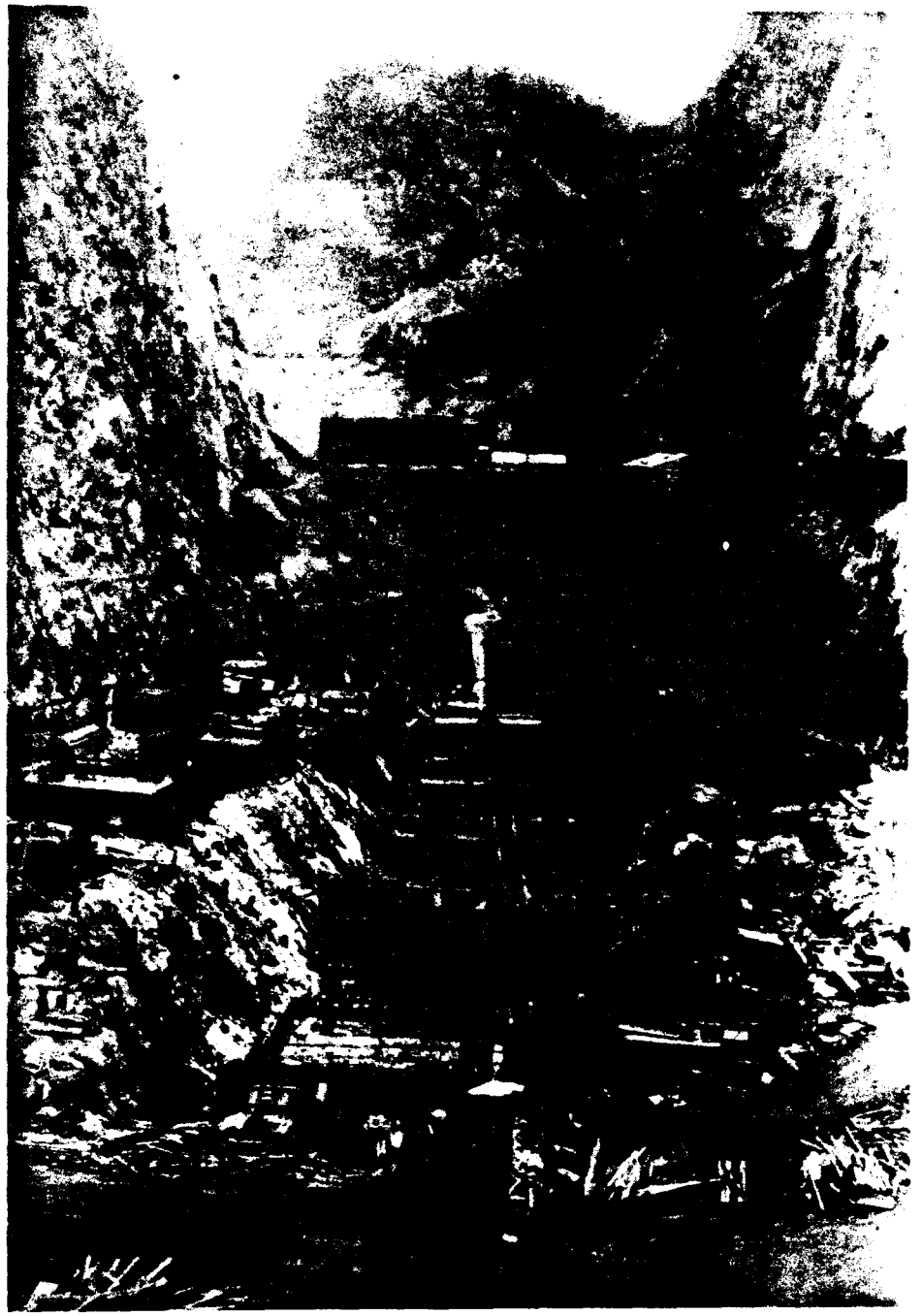
Numerous features, which today are attributed to valley stress relief, such as shear zones, platty rock, mud seams and hollow sounding rock slabs were observed in the floor and walls of the excavation, figure 9. These features did not parallel the bedding or other internal structures in the rock. During his inspection of the area Berkey[4] was apparently somewhat puzzled by such features, but quickly ruled out external causes, and wrote:

> "There seems to be no adequate external cause such as temperature changes, decay or progressive weakening, for there are many places equally exposed which do not show this effect at all. The inference is that some internal condition more obscure than ordinary is at the bottom of this behavior. This effect is believed due to the removal of support or load so that the rock is left in critical internal condition. There seems to be an attempt at readjustment within the rock mass resulting in slight expansion and rupturing. It is believed to be akin, in origin, to the so called "popping-rock" of many tunnels. The "hollow-rock" on the floor can be detected by pounding the floor which at these places "sounds hollow", due to the fact that a slab has sprung up enough to separate from the mass beneath."

7. Mud seams. A number of the sprung slabs were open enough to collect mud and were referred to as "mud seams". Again Berkey's report[4] reflects his deductive reasoning as follows:

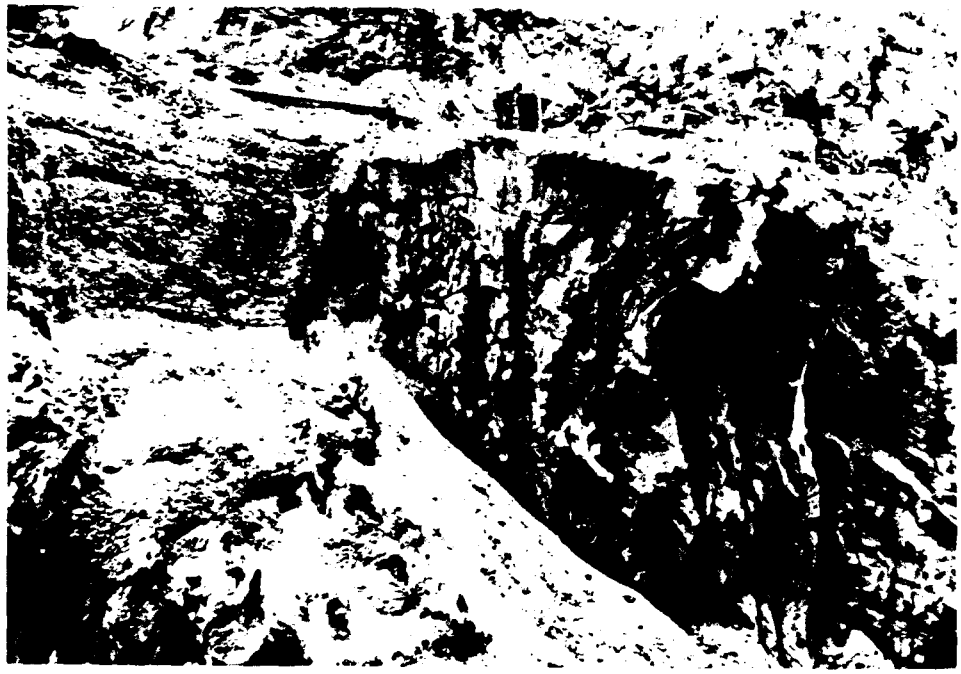
General view looking upstream at foundation excavation. Deeper middle channel is shown prior to any disturbance by blasting. The rock benches are at elevation 600. April 11, 1943.

Figure 7



Looking downstream in early stage in placement of dam concrete. July 18, 1933.

Figure 8



Characteristics of rock in walls of inner gorge. This photograph taken downstream looking at the Nevada side shows the flat bench (about elevation 600), the pot holing, scoring and fluting of the vertical wall of the inner gorge, and the stratified river fill at this level.

Cleavage structure of the so-called platy or slabby rock. The cleavage plates are nearly parallel to the free structure and do not follow the internal structure of the rock.

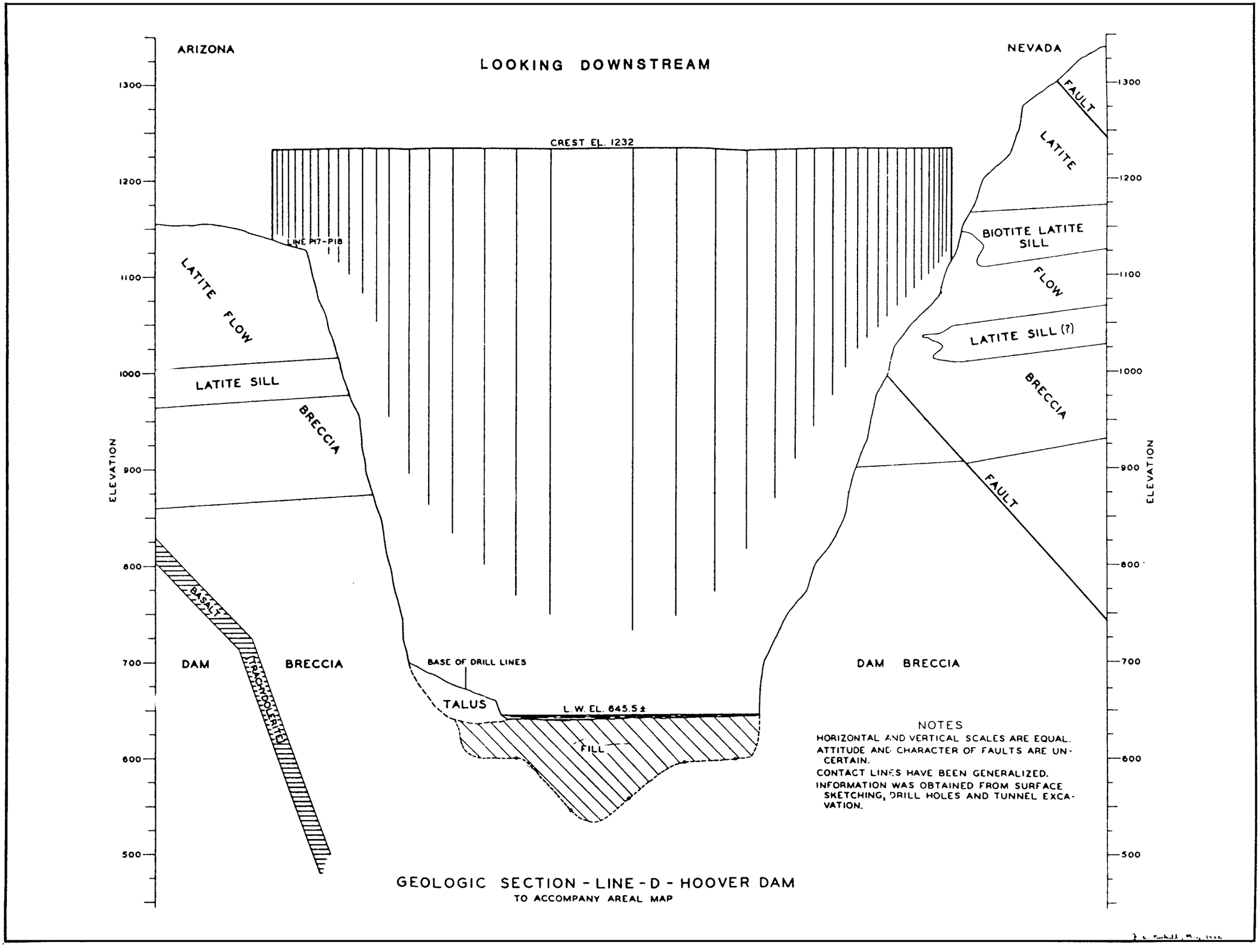
Photographs Nos. 13 and 18, Berkey's [4] report.

Figure 9

> "These mud seams may well represent an attempt of a somewhat deformed and over compressed portion of the rock mass forming the floor of the canyon to meet the new conditions of pressure and load under which the cutting of the gorge has placed it. The seam probably was not there at all before the gorge was cut. Probably the foundation should be excavated along all of these so called "mud seams" deeper than elsewhere and especially the flat lying ones, so as to reach comparatively tight ground."

During construction the steeper angled seams were cleaned of mud and loose or crushed rock, and where possible, backfilled with concrete and later grouted. The flat lying seams and "hollow-sounding" slabs were removed to sound rock.

8. Other rock defects. Although the dam was located so that its base occupied an area that was free from well defined faults, it was impossible to avoid some shear zones, fractures and a considerable number of joints related to the nearby faulting. These features are shown on maps of the abutments and foundation prepared by F. A. Nickell[5 and 6]. See figures 10 and 11. Every fracture that might influence the distribution of grout or permit passage of water was located and carefully examined. Many of these were merely seams or joints exhibiting little or no sign of movement. The nearest of the well-defined faults crossed the canyon floor upstream from the dam, and the other fault crossed the canyon floor downstream from the dam through the site of the power-plant. Most of the associated minor fractures dipped moderately to steeply downstream, from 17° to 59° southwest. The minor fractures within the area occupied by the dam composed two systems most of which had a strike approximately northwest and dipped 40° to 50° downstream. A second system, readily distinguished in the



GEOLOGIC SECTION - LINE - D - HOOVER DAM
TO ACCOMPANY AREAL MAP

FIGURE 10

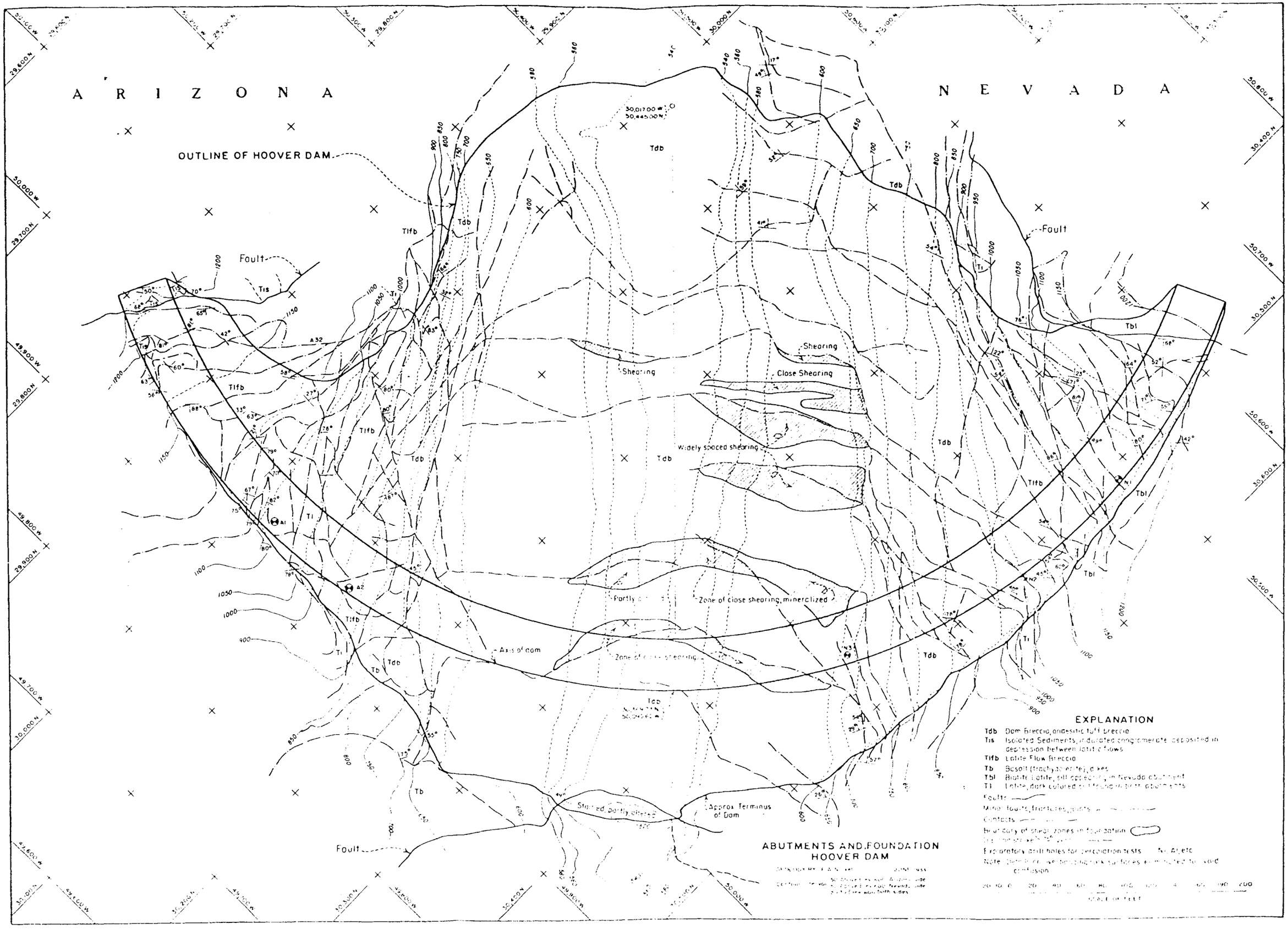

ARIZONA
NEVADA
OUTLINE OF HOOVER DAM
Fault
Tis
Tlfb
Tdb
Tl
Tb
Tbl
Shearing
Close Shearing
Widely spaced shearing
Zone of close shearing, mineralized
Axis of dam
Approx Terminus of Dam
A1
A2
N2
N3
EXPLANATION
Tdb Dam Breccia, andesitic tuff breccia
Tis Isolated Sediments, indurated conglomerate deposited in depression between latite flows
Tlfb Latite Flow Breccia
Tb Basalt (trachybasalt) dikes
Tbl Biotite latite, sill approaching in Nevada abutment
Tl Latite, dark colored [illegible] in both abutments
Fault
Minor faults, fractures, joints
Contacts
Boundary of shear zones in foundation
Exploratory drill holes for percolation tests
Note
confusion
ABUTMENTS AND FOUNDATION
HOOVER DAM

FIGURE 11

Arizona abutment, had a strike approximately north and dips were steeply inclined or vertical. It is not known whether the attitude, spacing and nature of these defects were taken into consideration in the design and installation of the grout curtain and drainage system.

IV. ORIGINAL GROUTING 1933-1935

9. General. Grouting during the original construction is described in Technical Memorandum No. 535 by V. L. Minear[7]. The general methods and equipment used for large concrete dams by the Bureau of Reclamation are described in a paper by Simonds, Lippold and Keim[8].

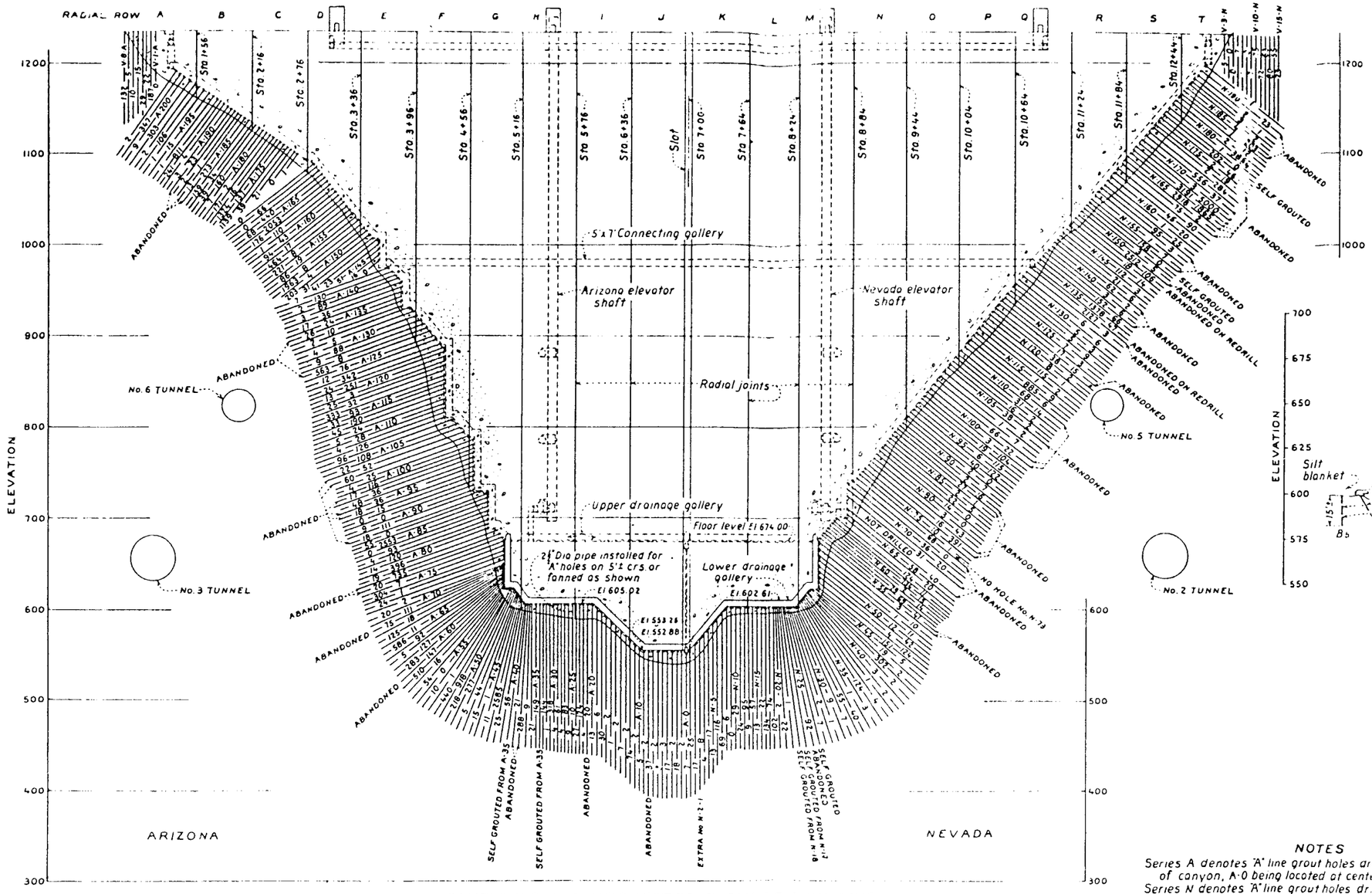
10. Design of the grout curtain. The treatment of the foundation involved a design based largely on experience and precedence in the foundation treatment for a number of large masonry dams, none of which were comparable in size to Hoover.

The position and inclination of the grout holes and a developed profile of the main cutoff curtain are shown on figure 12. The foundation grouting plan for the dam consisted of the following:

(1) Consolidation grouting along five lines of low pressure "B" holes roughly parallel to the axis in the upstream area of the foundation. Each line consisted of approximately 30 holes on 20-foot centers and were drilled to depths at from 30 to 50 feet. The holes were drilled normal to the rock surface.

(2) A single line of intermediate to high-pressure "C" holes drilled from the upstream edge of the dam on 10-foot centers. The holes were inclined in a downstream direction and drilled to a maximum depth of 125 feet or to within 20 feet of the "A" line.

(3) A cutoff curtain of high-pressure "A" holes drilled and grouted from the dam gallery on 5-foot spacing to a depth of 150 feet from the base of the dam up to elevation 675 feet. Above



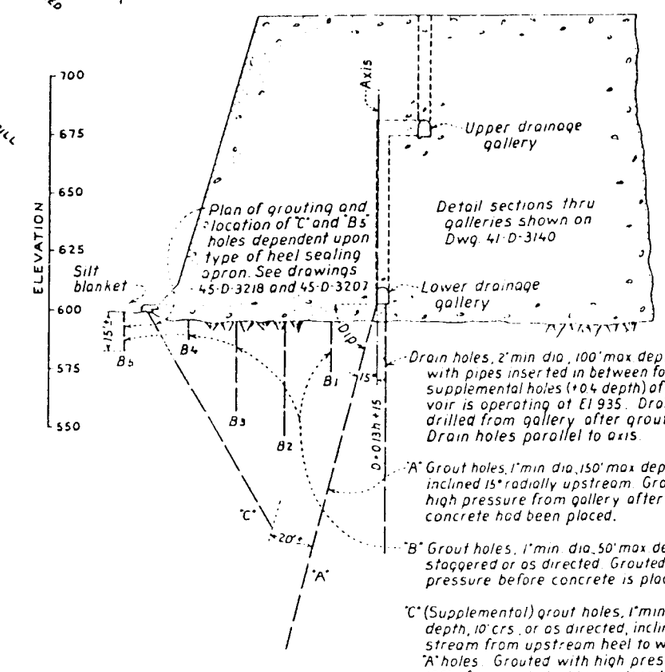
DEVELOPED AND PROJECTED ELEVATION ON AXIS
(APPROXIMATE)

CEMENT USED IN 'A' LINE GROUTING

SERIES OF HOLES	LIN FT OF HOLE	CEMENT USED, SACKS
A-0 to V-8-A	27,628.9	28,170
N-1 to V-15-N	27,161.6	31,483
Total for 414 holes	54,790.5	59,653
Average cement take per foot of hole		1.088 Sacks

REFERENCE DRAWINGS

PLAN OF GALLERIES AT EL 705.00	45-D-3137
FOUNDATION GROUTING BELOW EL 800.00	45-D-3138
FOUNDATION DRAINAGE SYSTEM BELOW EL 800.00	45-D-3139
FOUNDATION GROUTING AND DRAINAGE DETAILS	45-D-3140
INTERNAL DAM DRAINAGE SYSTEM	45-D-3141
LOWER DRAINAGE GALLERY	45-D-3142
LOWER DRAINAGE GALLERY DETAILS	45-D-3143
SUPPLEMENTAL GROUTING THRU FOUNDATION DRAINS	45-D-12993
FOUNDATION DRAINAGE AFTER COMPLETING SUPPLEMENTAL GROUTING	45-D-13566



Drain holes, 2" min dia., 100' max depth, 10' crs. with pipes inserted in between for drilling supplemental holes (+0.4 depth) after reservoir is operating at El 935. Drain holes drilled from gallery after grouting. Drain holes parallel to axis.

'A' Grout holes, 1" min dia., 150' max depth, 5' crs inclined 15° radially upstream. Grouted with high pressure from gallery after 100' of concrete had been placed.

'B' Grout holes, 1" min dia., 50' max depth, 20' crs staggered or as directed. Grouted with low pressure before concrete is placed.

'C' (Supplemental) grout holes, 1" min dia., 100' max depth, 10' crs., or as directed, inclined downstream from upstream heel to within 20' of 'A' holes. Grouted with high pressure after 100' of concrete had been placed and after 'A' holes have been grouted. Alternate holes to be first drilled and grouted; intermediate holes later drilled and grouted, if required.

SECTIONAL ELEVATION ON RADIAL PLANE

NOTES

Series A denotes 'A' line grout holes drilled on Arizona side of canyon, A-0 being located at center of slot.
Series N denotes 'A' line grout holes drilled on Nevada side of canyon.
Hole number is prefixed by series letter, and number of sacks of cement injected is determined by figure near end of hole thus: ——N-50——12——
Abandoned holes were those where grouting was prematurely terminated because of leaks or other trouble
Holes redrilled at Government expense
A-Series: 164, 165, 173, 174, 175, 176 total footage 669.5'
N-Series: 133, 134, 135, 136, 148, 149, 165, 166, 161 total footage 1263.0'
Redrilled holes were offset 12' or more from original location
Quantities for drilling and grouting redrilled holes are included in table

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
BOULDER CANYON PROJECT

BOULDER DAM

RECORD OF GROUTING OF "A" LINE HOLES BY CONTRACTOR - 1934-5

DRAWN S.W.B. SUBMITTED G. W. Simonds
TRACED T.M. RECOMMENDED [illegible]
CHECKED [illegible] APPROVED [illegible]
DENVER, COLORADO, FEB 25, 1935 45-D-14155

FIGURE 12

elevation 675, the depth of the holes was decreased uniformly to 100 feet at elevation 1,200. The "A" holes were inclined 15 degrees in an upstream direction.

The order of grouting the different lines was "B", "A", and "C". The "A" line grouting was not started until at least 100 feet of concrete had been placed over the site of the hole.

11. Specifications. The specifications were complete insofar as general performance of work to be accomplished was concerned and apparently were not the cause of any major construction difficulties. The only suggestion of possible claim was that the Contractor at Boulder Dam maintained that he was under no obligation "to search for, report the discovery of, or calk grout leaks."

12. Drilling. Percussion-type drills such as jackhammers and wagon drills were used to drill the shallow, low-pressure grout holes. Jackhammers were used for collaring all diamond drill holes and for drilling the 30-foot holes of the "B" lines and wagon drills were used for drilling the 40- and 50-foot deep "B" holes. An air driven diamond drill, using 7/8" to 15/16" bortz, plug type bits were used to drill some of the "B" holes and all of the "A" and "C" holes after collaring the holes with jackhammers.

13. Water-pressure tests. The specifications required that prior to grouting, the hole was to be thoroughly washed under continuous pressure as required by the contracting officer up to the required grouting pressure.

14. Grout mixes. The consistency of grout mixes was variable, ranging from water-cement ratios of 5:1 to 1:1 by volume

in the grouting of "B" holes and faults to 7:1 to 0.75:1 in the "C" and "A" holes. The specifications permitted the use of sand but only neat cement grout mixes were used in the operations.

According to Minear[7] a rule-of-thumb method used to determine the initial grout mix was as follows:

> "initial injections should be of a grout having a water-cement ratio equal to 0.01P where P was the limiting pumping pressure. Thus a 500 p.s.i. hole would be started with a grout whose water-cement ratio by volume was 5:1."

According to Minear[7], the rule of thumb "worked well at Boulder Dam." See appendix C for discussion on the grout-mix procedures.

15. Grout-injection pressures. According to the specifications, pressures of not less than 100 p.s.i. and not more than 300 p.s.i. were to be used in the grouting of the foundations for the dam, spillway crest and inlet structures for the outer diversion tunnels. The unit grout pressure required for all pressures above the minimum of 100 p.s.i. was to be determined by the contracting officer on the basis of the full reservoir hydrostatic head at the elevation of the grouting connection plus an addition of 50 p.s.i. The pressures used in construction were as follows:

(1) For consolidation or low pressure grouting of "B" holes, pressures ranged from 300 to 400 p.s.i.

(2) For supplemental curtain "C" holes, pressure ranged from 500 to 750 p.s.i.

(3) For "A" line holes or high pressure grouting, the following rules governed the injection of grout.

Below elevation 800.	1000 p.s.i.
From elevation 800 to 1000 . . .	750 p.s.i.
Above elevation 1000	500 p.s.i.

Grouting of the "A" line was not started until at least 100 feet of concrete was placed over the site of the hole and cooled and until after the contraction joints were grouted.

16. Spacing of holes and closure. The spacing or sequence of drilling and grouting is not given in the specifications or in any of the reports on grouting. Figure 12 indicates that "B" holes on 20-foot centers were to be staggered as directed and that on the "C" line, alternate holes were to be first drilled and grouted; intermediate holes later drilled and grouted if required. Pattern closure was 10-foot centers. This suggests that primary holes on the "C" line were drilled and grouted on 20-foot spacing with closure to 10 feet with closer spacing on final closure as required. Closure for "A" line holes was to 5-foot centers. No zones or predetermined partial depth of curtain to be grouted are shown. This indicates that grouting was single stage from the collar (nipple) to the bottom of the hole.

The cement take per foot of hole for "B" line drilling and grouting is taken from Table 3 of Minear's Report[7] and is as follows:

NEVADA SIDE

No.of holes	Nom-inal	Depth Total	Depth Avg.	Cement-sacks Total	Cement-sacks Per hole	Cement-sacks Per foot	Remarks
36	30	1055.5	29.31	2360	65.55	2.235	25NB1 took 1426 sax
12	40	489.5	40.79	1558	129.8	3.182	12NB3 took 1308 sax
20	50	942.1	47.10	686	34.3	0.728	

ARIZONA SIDE

37	30	1130.3	30.54	1405	37.97	1.243	
16	40	589.1	36.82	465	29.06	0.789	
22	50	1006.6	45.75	190	8.63	0.188	

TOTAL

73	30	2185.8	29.94	3765	51.57	1.722
28	40	1078.6	38.52	2023	72.25	1.875
42	50	1948.7	46.40	876	20.85	0.449
143	-	5213.1	36.45	6664	46.60	1.278

The "C" line sequence of drilling and grouting and the grout takes are not shown in the records. The records indicate that the "C" holes were not installed above El. 750.

The data tabulated for the "A" line of holes by Minear[7] are as follows:

Grouting	No. of holes	No. of sacks	Sacks per hole
Nevada Side:			
Primary	63	25,691	408
1st Intermediate	62	1,966	31
2nd Intermediate	40	586	14
3rd Intermediate	23	243	10
Arizona Side:			
Primary	55	15,596	283
1st Intermediate	34	5,925	174
2nd Intermediate	26	1,093	42
3rd Intermediate	22	1,092	50
4th Intermediate	5	380	76
5th Intermediate	2	196	98

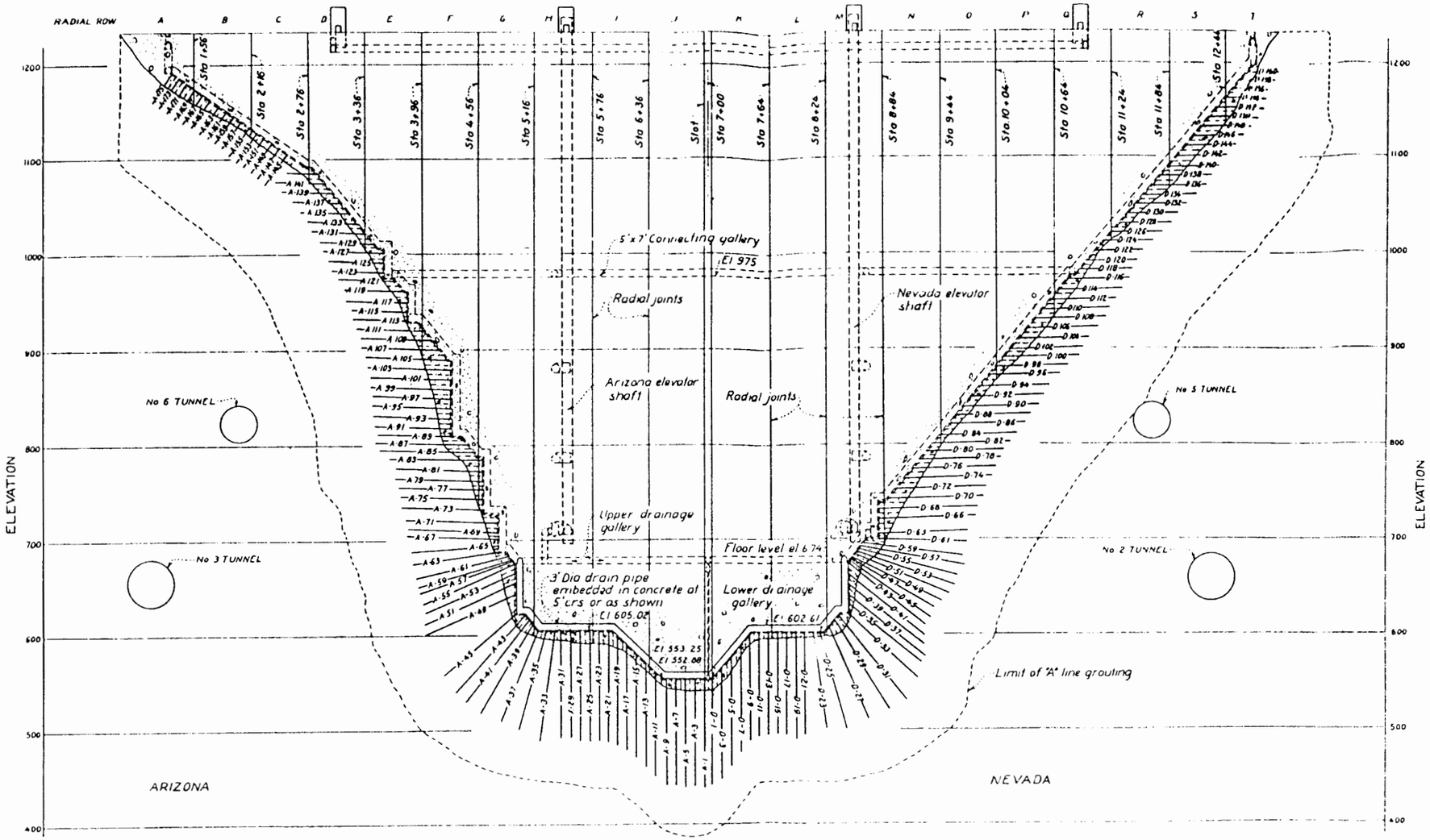
The unit take values were not shown in the tabulation; however, on the Nevada side, the progressive decrease in sacks per hole from primary through 3rd intermediate indicates the rock was tighter due to grouting. The data show a different picture on the Arizona side where the 3rd through 5th order splits accepted more sacks per hole than those of the 2nd order. In addition, the total of sacks per hole in the closure splits (3rd through 5th order) was 224 sacks which is more than the total for the first and second order holes and almost as much as the primary holes. This indicates that either grouting in the initial phase was not effective or that possibly lifting, excessive surface leakage or both occurred in grouting the closure holes. In any case, with grout takes of an average of 98 sacks per hole on the final closure, grouting was discontinued before the curtain had been adequately tightened.

Records indicate that grout leakage from the "A" holes into the abutment contact grouting system occurred frequently. When this occurred, the usual procedure was to stop grouting, wash out the system and abandon the hole. Of 414 holes in the "A" line curtain, 52 or 12.5 percent of the holes were abandoned before completion due to leakage of one kind or another. See figure 12. Four of the holes on the Nevada side (Holes N-165 through N-168) all on 5-foot centers were abandoned after accepting a total of 12,974 sacks of cement. In addition, many holes in the warm springs were lost in that they refused to accept grout. The warm water caused the grout to flash set as soon as the grout was injected.

17. Refusal criteria. The specifications required that grouting shall not be stopped in any hole until the hole takes grout at the rate of not more than one cubic foot in ten minutes when the required grouting pressure is applied.

18. Backfill methods. The specifications did not require that the completed grout holes be sounded to determine if the grout had shrunk and left voids.

19. Foundation drains. Most of the information available on the drilling of the original drainage curtain is shown on figure 13 which was reproduced from figure 9 of Simonds and Boggess'[6] report. These data indicate that the holes were drilled in the radial plane of the dam. The holes were 2 inches in diameter and ranged in depth from about 100 feet in the bottom of the canyon to about 20 feet near the top of the dam. The drains were discharging about 200 gpm in September, 1938.



DEVELOPED AND PROJECTED ELEVATION ON AXIS
(APPROXIMATE)

REFERENCE DRAWINGS

FOUNDATION GROUTING ABOVE El 800	45-D-2536
PLAN OF GALLERIES AT El 705.00	45-D-3137
FOUNDATION GROUTING BELOW El 800	45-D-3138
FOUNDATION DRAINAGE SYSTEM BELOW El 800	45-D-3139
FOUNDATION GROUTING AND DRAINAGE DETAILS	45-D-3140
INTERNAL DAM DRAINAGE SYSTEM	45-D-3141
LOWER DRAINAGE GALLERY	45-D-3142
LOWER DRAINAGE GALLERY DETAILS	45-D-3143

DEPTH OF DRAIN HOLES

ARIZONA SIDE				NEVADA SIDE			
HOLE	DEPTH	HOLE	DEPTH	HOLE	DEPTH	HOLE	DEPTH
A-1	100.5	A-89	69.7	D-1	101.0	D-90	65.8
A-3	101.0	A-91	68.4	D-3	100.5	D-92	64.5
A-5	102.4	A-93	67.1	D-5	100.0	D-94	63.2
A-7	101.2	A-95	65.8	D-7	101.0	D-96	61.9
A-9	101.0	A-97	64.5	D-9	102.0	D-98	60.6
A-11	100.0	A-99	63.2	D-11	102.0	D-100	59.3
A-13	100.0	A-101	61.9	D-13	101.0	D-102	58.0
A-15	100.0	A-103	60.5	D-15	101.0	D-104	56.7
A-17	100.0	A-105	59.3	D-17	101.0	D-106	55.4
A-19	101.0	A-107	58.0	D-19	105.2	D-108	54.1
A-21	101.7	A-109	56.7	D-21	102.0	D-110	52.8
A-23	99.2	A-111	55.4	D-23	95.3	D-112	51.5
A-25	101.0	A-113	54.1	D-25	98.5	D-114	50.2
A-27	101.8	A-115	52.8	D-27	97.2	D-116	48.9
A-29	97.5	A-117	55.1	D-29	97.1	D-118	47.6
A-31	101.2	A-119	50.2	D-31	95.9	D-120	46.3
A-33	106.0	A-121	48.9	D-33	94.7	D-122	45.0
A-35	97.5	A-123	47.6	D-35	93.6	D-124	43.7
A-37	97.3	A-125	46.3	D-37	93.0	D-126	42.6
A-39	97.9	A-127	45.0	D-39	90.8	D-128	41.1
A-41	97.5	A-129	43.7	D-41	89.7	D-130	39.8
A-43	95.4	A-131	42.4	D-43	89.9	D-132	38.5
A-45	94.0	A-133	41.1	D-45	89.0	D-134	37.2
A-47	—	A-135	39.8	D-47	88.5	D-136	35.9
A-49	91.6	A-137	38.5	D-49	88.6	D-138	34.6
A-51	90.2	A-139	37.2	D-51	87.5	D-140	33.3
A-53	89.8	A-141	35.9	D-53	86.8	D-142	32.0
A-55	88.4	A-143	15.0	D-55	86.4	D-144	30.7
A-57	88.0	A-145	32.4	D-57	87.0	D-146	29.4
A-59	87.4	A-147	31.5	D-59	86.9	D-148	28.1
A-61	86.7	A-149	30.7	D-61	86.5	D-150	26.8
A-63	86.2	A-151	30.2	D-63	83.9	D-152	25.5
A-65	85.4	A-153	29.4	D-66	84.0	D-154	24.2
A-67	86.0	A-155	28.8	D-68	80.1	D-156	22.9
A-69	82.6	A-157	28.0	D-70	78.8	D-158	21.6
A-71	81.4	A-159	27.0	D-72	77.5	D-160	20.3
A-73	80.1	A-161	26.4	D-74	76.2		
A-75	78.8	A-163	25.7	D-76	74.9		
A-77	77.4	A-165	25.1	D-78	73.6		
A-79	76.2	A-167	24.4	D-80	72.3		
A-81	75.9	A-169	23.7	D-82	71.0		
A-83	74.6	A-171	23.1	D-84	69.7		
A-85	73.3	A-173	22.4	D-86	68.4		
A-87	71.0	A-175	21.8	D-88	67.1		

Linear ft of hole drilled Arizona side ..... 5819.8'
Linear ft of hole drilled Nevada side ..... 5463.9'
Total depth of drain holes drilled ..... 11,283.7'

NOTES

Drain holes were drilled 2" in diameter.
Depths of drain holes are shown on dwgs 45-D-2536 and 45-D-3139, maximum depth 100'.
No payment was allowed for drilling in excess of authorized depth.
Actual depths to which holes were drilled are shown in table.

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
BOULDER CANYON PROJECT

BOULDER DAM

RECORD OF DRAINAGE HOLES DRILLED BY CONTRACTOR IN 1935

DRAWN A.W.S. SUBMITTED D. W. Simonds
TRACED T.M.N. RECOMMENDED T. O. Ellgen
CHECKED ADK APPROVED W. H. Nelder

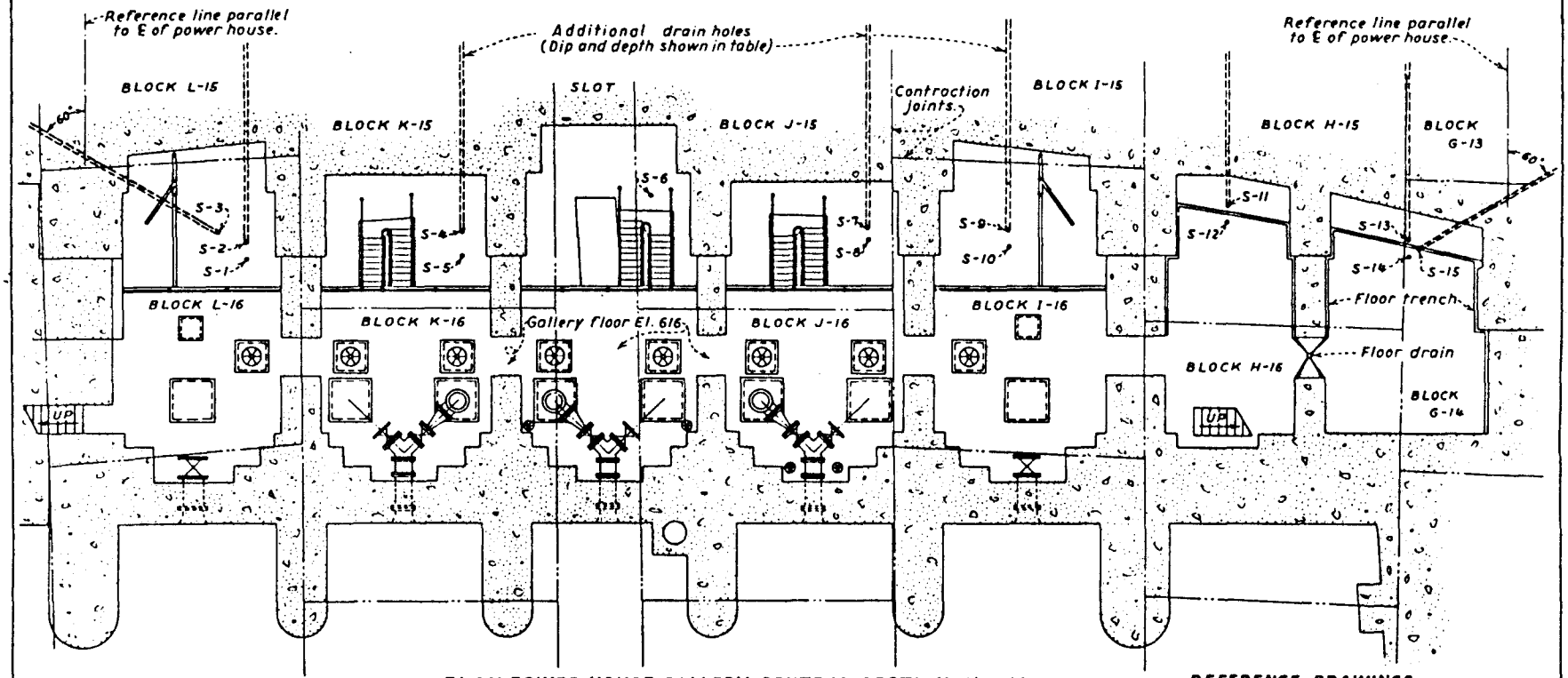
DENVER, COLORADO MARCH 2, 1938 45-D-14159

FIGURE 13

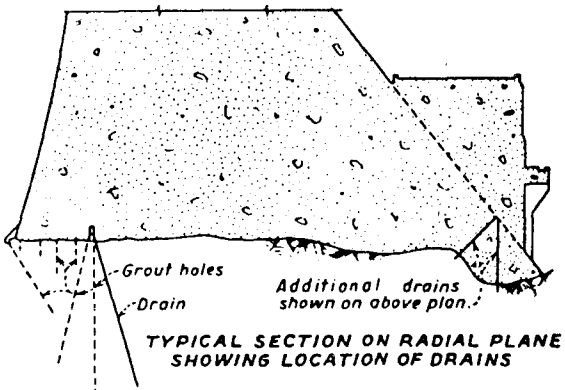
V. ADDITIONAL GROUTING 1938-1947

24. General. The work included grouting of the dam foundation from the grouting galleries and from appurtenant structures and also included installation of new drain holes for the dam and for some appurtenant structures. This work has been described in detail by Simonds and Boggess[6] and by Simonds[9], and only a brief description of the work will be presented herein.

The initial work started in October, 1938, with drilling of 15 drain holes from the El. 616 gallery of the powerhouse into the foundation near the downstream toe of the dam. See figure 14. These drains penetrated 5 feet into rock and did lower the uplift pressures in line C but not in line B. Attempts were made without success to regrout nine Nevada A holes that penetrated the fault zone between El. 840 and El. 940. Drilling of alternate drain holes on 10-foot centers (which had not been drilled during the original construction) between Stations 5+46 and 8+04 in the El. 553 drainage gallery disclosed mud seams extending beneath the river channel at El. 525. Broken rock was found at El. 500±, and a large flow of water was encountered at El. 405. It was decided to deepen the original drain holes and to convert them into a grout curtain and to later install a new drainage system downstream. Twenty-five of the new grout holes were core drilled which gave considerable additional information on the foundation conditions. Hole D-23 was drilled to a depth of 479.8 feet and was the deepest hole drilled. As shown on figure 15, many of the holes were drilled to 400 feet into rock and most of the holes in



PLAN POWER HOUSE GALLERY, CENTRAL SECTION EL. 616



TYPICAL SECTION ON RADIAL PLANE SHOWING LOCATION OF DRAINS

ADDITIONAL DRAIN HOLE DATA

HOLE	DIP DEGREES	DEPTH FEET
S-1	-90	145
S-2	-45	164
S-3	-60	105
S-4	-45	168
S-5	-90	147
S-6	-90	138
S-7	-45	165
S-8	-90	125
S-9	-45	162
S-10	-90	133
S-11	-45	116
S-12	-90	128
S-13	-45	103
S-14	-90	124
S-15	-60	92

REFERENCE DRAWINGS

CONTRACTION JOINT LAYOUT, GENERAL PLAN 45-D-2318
BOULDER POWER PLANT, CENTRAL PORTION, PLAN AT EL. 620+, FLOOR EL. 616.0 ..... 45-D-4601

NOTES

Additional drainage holes were drilled from downstream face of dam opposite El. 616 gallery floor.
Holes were drilled with 2½" dia. bit 3' into foundation rock.

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
BOULDER CANYON PROJECT

BOULDER DAM

ADDITIONAL DRAINAGE HOLES DRILLED THRU DOWNSTREAM TOE OF DAM

DRAWN A.W.S. SUBMITTED R. W. Simonds
TRACED E.D.L. RECOMMENDED T. V. Rennie
CHECKED A.D.K. APPROVED W. H. Nalder

DENVER, COLORADO APRIL 20, 1945 | 45-D-14163

FIGURE 14

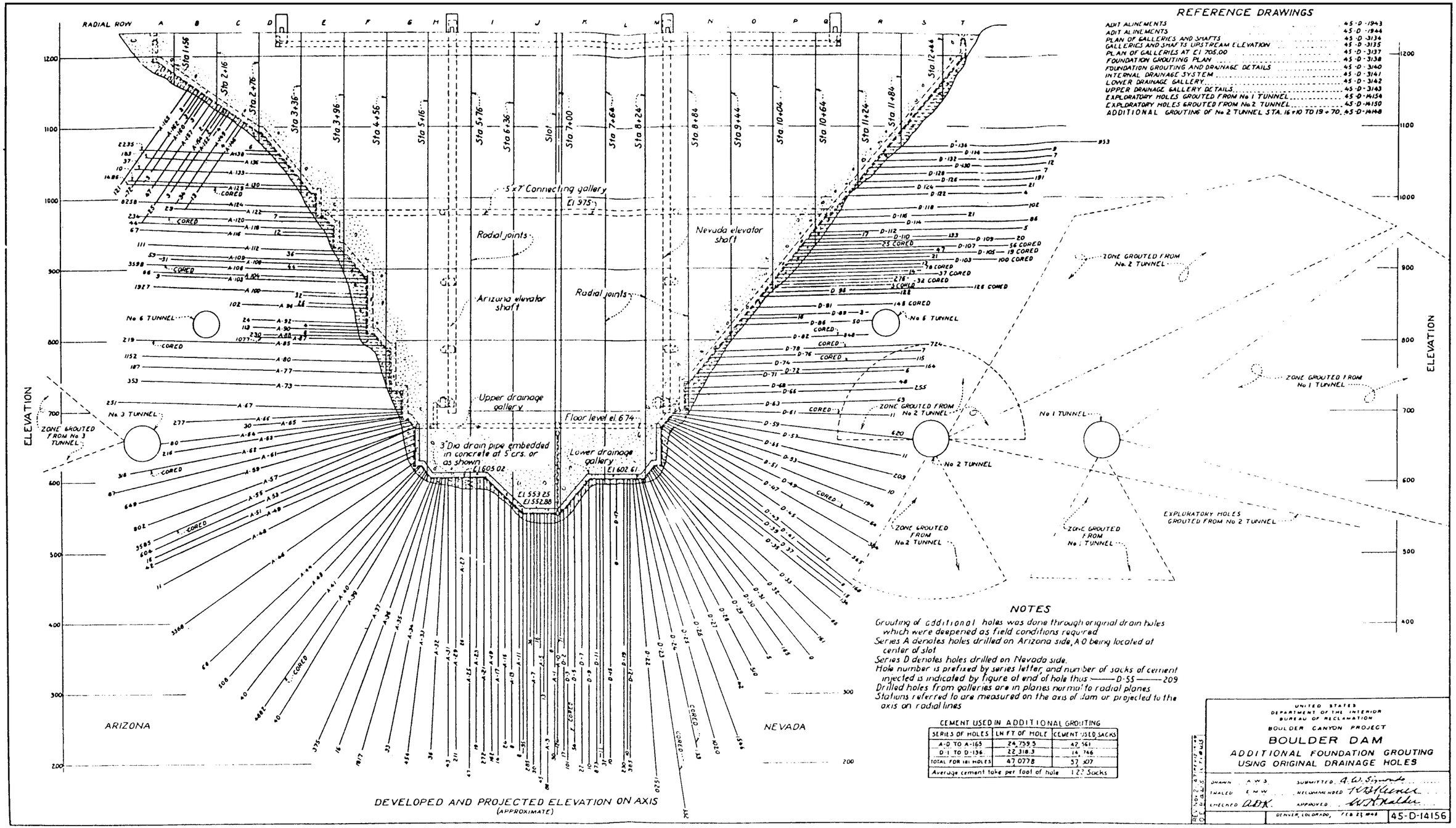

REFERENCE DRAWINGS
ADIT ALINEMENTS 45-D-1943
ADIT ALINEMENTS 45-D-1944
PLAN OF GALLERIES AND SHAFTS 45-D-3134
GALLERIES AND SHAFTS UPSTREAM ELEVATION 45-D-3135
PLAN OF GALLERIES AT El 705.00 45-D-3137
FOUNDATION GROUTING PLAN 45-D-3138
FOUNDATION GROUTING AND DRAINAGE DETAILS 45-D-3140
INTERNAL DRAINAGE SYSTEM 45-D-3141
LOWER DRAINAGE GALLERY 45-D-3142
UPPER DRAINAGE GALLERY DETAILS 45-D-3143
EXPLORATORY HOLES GROUTED FROM No 1 TUNNEL 45-D-14154
EXPLORATORY HOLES GROUTED FROM No 2 TUNNEL 45-D-14150
ADDITIONAL GROUTING OF No 2 TUNNEL STA. 16+10 TO 19+70 45-D-14148
RADIAL ROW
ELEVATION
5'x7' Connecting gallery El 975
Radial joints
Nevada elevator shaft
Arizona elevator shaft
Upper drainage gallery
Floor level el 674
3" Dia drain pipe embedded in concrete at 5' crs. or as shown
Lower drainage gallery
No 6 TUNNEL
No 3 TUNNEL
No 2 TUNNEL
No 1 TUNNEL
ZONE GROUTED FROM No 3 TUNNEL
ZONE GROUTED FROM No 2 TUNNEL
ZONE GROUTED FROM No 1 TUNNEL
EXPLORATORY HOLES GROUTED FROM No 2 TUNNEL
ARIZONA
NEVADA
DEVELOPED AND PROJECTED ELEVATION ON AXIS
(APPROXIMATE)
NOTES
Grouting of additional holes was done through original drain holes which were deepened as field conditions required
Series A denotes holes drilled on Arizona side, A 0 being located at center of slot
Series D denotes holes drilled on Nevada side.
Hole number is prefixed by series letter, and number of sacks of cement injected is indicated by figure at end of hole thus ——D-55——209
Drilled holes from galleries are in planes normal to radial planes
Stations referred to are measured on the axis of dam or projected to the axis on radial lines
CEMENT USED IN ADDITIONAL GROUTING
SERIES OF HOLES | LIN FT OF HOLE | CEMENT USED SACKS
A-0 TO A-165 | 24,759.5 | 42,561
D-1 TO D-136 | 22,318.3 | 14,746
TOTAL FOR 181 HOLES | 47,077.8 | 57,307
Average cement take per foot of hole 1.22 Sacks
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
BOULDER CANYON PROJECT
BOULDER DAM
ADDITIONAL FOUNDATION GROUTING
USING ORIGINAL DRAINAGE HOLES
DRAWN A.W.S.
TRACED E.N.W.
CHECKED
SUBMITTED
RECOMMENDED
APPROVED
DENVER, COLORADO, FEB 23 1948
45-D-14156

FIGURE 15

the canyon bottom were over 300 feet deep, which was more than twice the depth of the original holes.

Other areas grouted include between intake towers and Nevada spillway tunnel, the upstream end of No. 2 tunnel, the Nevada abutment to right of No. 2 and No. 1 tunnels, the Nevada abutment from tunnel No. 1, the Nevada spillway, and the Arizona abutment from No. 3 tunnel. Drilling and grouting for these auxiliary facilities effectively extended the dam grout curtain into the abutments and materially contributed to the overall seepage barrier at the site.

25. Procedures. High water flows with high pressures were encountered in many holes. See figure 16. Special packers and equipment were developed to shut off the water when grouting was started. Considerable flexibility was used in grouting the holes. Some holes were grouted in one stage; other holes were grouted in descending stages without packers set at the end of the preceeding stage. Several holes or stages were cleaned out and regrouted. Grouting was only done on the day shift. When a hole required more than one day to grout, water was circulated in the hole at the end of the day, and this evidently kept the hole open for grouting the next day.

Of particular interest was the search for a cement that would not flash set when hot alkaline water was encountered. It was found that a special finely ground oilwell cement could be used in areas of hot alkaline water. After the War Production Board issued an order prohibiting the cement manufacturers from making special grinds, it was found that a suitable injectable mixture

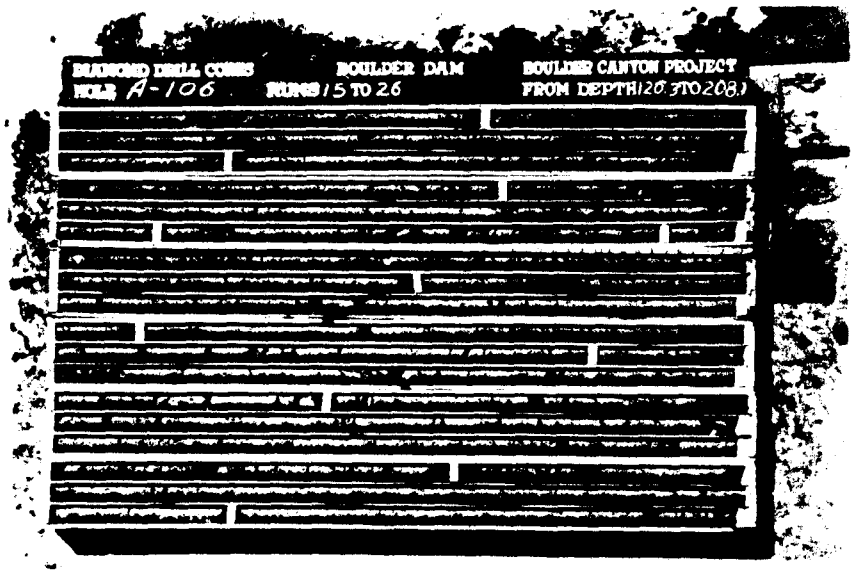
Water flow from A-9

Flow from exploratory hole in No. 1 tunnel station 19 + 70, horizontal; Ex size, depth 192'; estimated flow 400 gpm; hole was grouted in stages to depth of 178' and this flow was picked up in 14' of hole when drilling the next stage.

Figure 16

could be obtained for warm water areas by using a commercial retarder known as S.R.D.A. mixed in proportions of 1 lb. to 6 sacks of modified cement.

The grouting disclosed hydraulic connections in both the horizontal and vertical directions. Hole D-23 tapped a shear zone at a depth of about 400 feet (El. 200±) which was the source of water appearing on the Nevada abutment between El. 830 and El. 940. Injection of grout into hole D-23 caused an increase in uplift in all the observation pipes and caused an increase in flow from drain hole D-100 located at El. 890 on the Nevada abutment. Later when D-100 was dosed with flourescein, discoloration appeared in the return flows of holes A-1 and D-1 located in the El. 553 gallery beyond D-23. Hole A-55 was originally drilled as a drain hole 88.4 feet deep. It was extended to a depth of 398.4 feet and grouted in one stage, and after 3,400 sacks of cement had been injected, grout leaks appeared in tunnel No. 3 which was over 100 feet in elevation above A-55. Hole A-138 was drilled 200 feet deep and grouted in one stage with 2,235 sacks of cement. Drill water was lost before the 200 foot depth. No back pressure developed during injection of the first 1,500 sacks indicating that the grout was traveling down into an open void. When pressure developed grout broke out in a large fault along the highway curb 175 feet in elevation above the hole. These are just a few examples of the extensive hydraulic connections found during the drilling and grouting operations. The core of hole A-106 is shown on figure 17.



Core from hole A-106. Hole A-106 was drilled and grouted in two stages. It was drilled 181 feet deep in December 1942 and grouted with 142 sacks of cement. It was subsequently deepend to 298.2 feet and grouted with 3,456 sacks of cement March 1943.

Figure 17

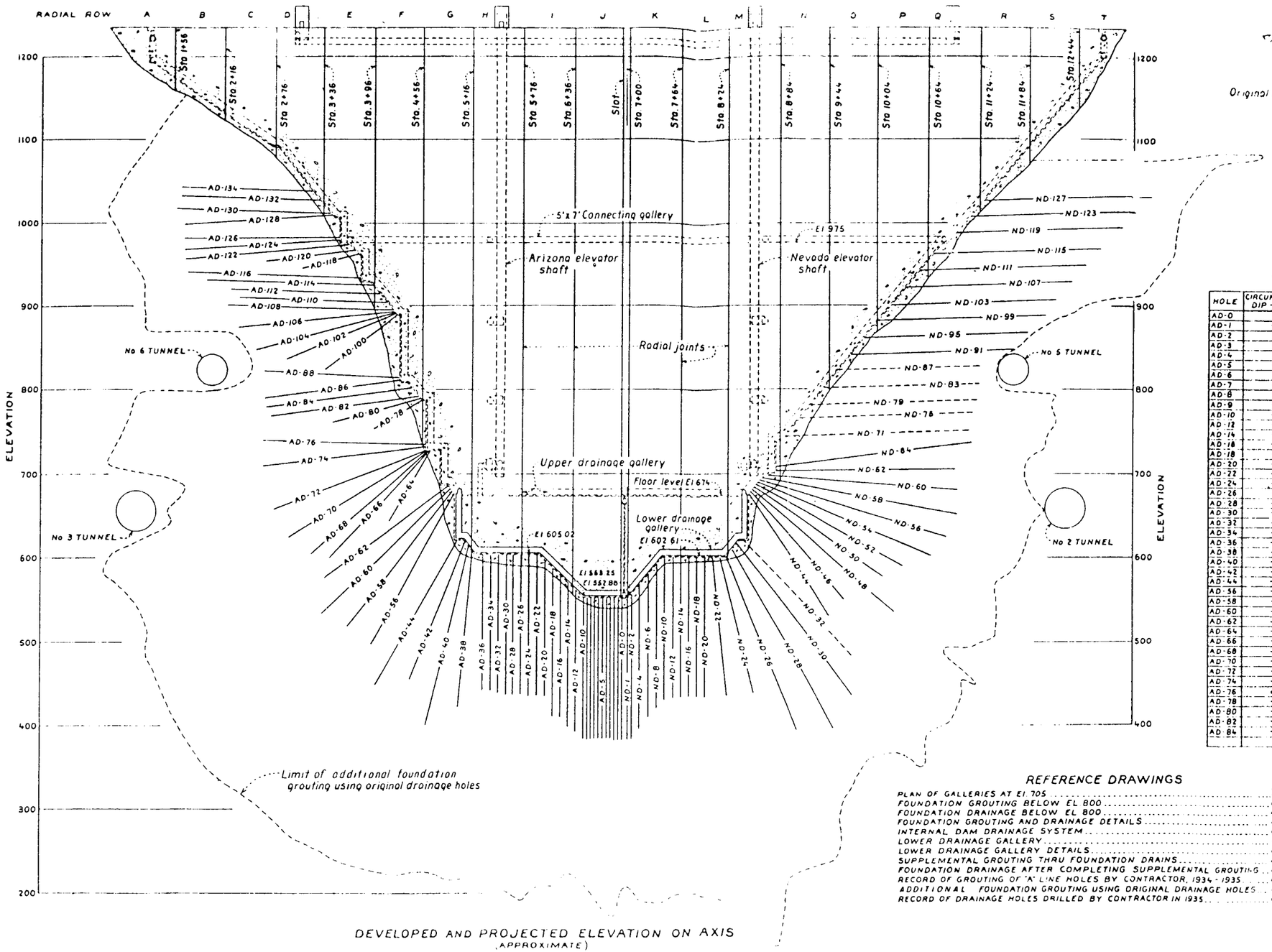
26. Water-cement ratios. In general, water-cement ratios ranged from 15:1 to 5:1 although some mixes of 20:1 were used. At the beginning the program, the water-cement ratios varied from 7:1 to 3:1 but thinner mixes of 10:1 to 4:1 were used more frequently as work progressed. In fairly tight rock, many of the holes were grouted with mixes having water-cement ratios of 20:1, 14:1, and 12:1. Unless surface leaks developed, grout thicker than 7:1 was rarely used. Thinner grout mixes were found to be more successful for "squeezing off seepage".

27. Grouting pressures. Grout injection pressures generally ranged from 550 to 600 p.s.i. The maximum pressures used were about 750 p.s.i.; however, Simonds[9] indicated that pressures as high as 1,000 p.s.i. were used in a few holes.

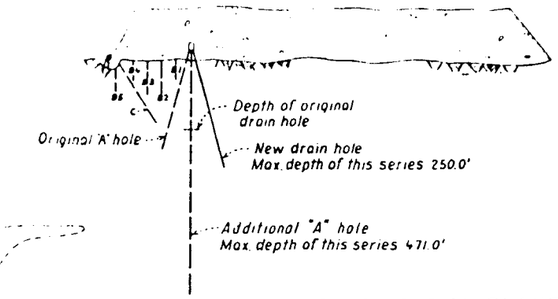
28. Spacing and closure. The sequence of drilling and grouting is not given in any of the grouting reports; however, Simonds[9] stated that:

> "the method of closures was adopted as the optimum method of procedure. In this method, the primary holes were drilled and grouted at fairly wide spacing. The next holes were drilled and grouted halfway between the primary holes and this procedure continued until the amount of grout used indicated that the foundation was tight."

29. Drain holes. New drains were drilled from the grout and drainage gallery. See figure 18. The holes were drilled at an angle 15° downstream from the original line. They were drilled to a maximum depth of 250 feet and were of EX size (1-1/2 inch). In general the holes were drilled to a depth that their effect was noticeable in the uplift pipes. The flow from the drains was appreciable and amounted to 2,030 gpm in September and October,



DEVELOPED AND PROJECTED ELEVATION ON AXIS
(APPROXIMATE)



SECTIONAL ELEVATION ON RADIAL PLANE

DEPTHS OF ADDITIONAL DRAIN HOLES

ALL HOLES ANGLE 15° DOWNSTREAM WITH ORIGINAL DRAINS

ARIZONA SIDE						NEVADA SIDE		
HOLE	CIRCUMFERENTIAL DIP - DEGREES	DEPTH IN FT.	HOLE	CIRCUMFERENTIAL DIP - DEGREES	DEPTH IN FT.	HOLE	CIRCUMFERENTIAL DIP - DEGREES	DEPTH IN FT.
AD-0	-90	170	AD-86	-7	165	ND-1	-90	170
AD-1	-90	170	AD-88	+2	165	ND-2	-90	177
AD-2	-90	170	AD-100	-37	110	ND-4	-90	172
AD-3	-90	170	AD-102	-23	145	ND-6	-90	170
AD-4	-90	170	AD-104	-14	175	ND-8	-90	170
AD-5	-90	171	AD-106	-6	170	ND-10	-90	170
AD-6	-90	170	AD-108	+2	200	ND-12	-90	170
AD-7	-90	170	AD-110	+2	180	ND-14	-90	170
AD-8	-90	170	AD-112	+2	180	ND-16	-90	170
AD-9	-90	170	AD-114	+2	200	ND-18	-90	170
AD-10	-90	170	AD-116	+2	210	ND-20	-90	170
AD-12	-80	170	AD-118	-14	70	ND-22	-84	170
AD-14	-90	175	AD-120	-7	118	ND-24	-78	170
AD-16	-90	170	AD-122	-5	200	ND-26	-68	225
AD-18	-90	181	AD-124	-3	190	ND-28	-60	240
AD-20	-90	170	AD-126	+2	190	ND-30	-52	230
AD-22	-90	170	AD-128	-4	180	ND-32		
AD-24	-90	170	AD-130	+2	190	ND-44	-56	171
AD-26	-90	170	AD-132	+2	170	ND-46	-48	170
AD-28	-90	170	AD-134	+2	160	ND-48	-40	225
AD-30	-90	170				ND-50	-34	190
AD-32	-90	170				ND-52	-28	202
AD-34	-90	170				ND-54	-22	230
AD-36	-90	170				ND-56	-16	238.2
AD-38	-84	182				ND-58	-10	266
AD-40	-78	222				ND-60	-4	236
AD-42	-68	178				ND-82	+2	230
AD-44	-60	204				ND-64	+8	252
AD-56	-60	206				ND-71		
AD-58	-52	205				ND-75		
AD-60	-44	216				ND-79		
AD-62	-36	186.6				ND-83		
AD-64	-60	99.2				ND-87		
AD-66	-48	175				ND-91	+2	200
AD-68	-43	190				ND-95	+2	200
AD-70	-33	200				ND-99	+2	200
AD-72	-21	200				ND-103	+2	200
AD-74	-7	200				ND-107	+2	200
AD-76	+20	200				ND-111	+2	142
AD-78	-30	65				ND-115	+2	200
AD-80	-15	110				ND-119	+2	200
AD-82	-10	180				ND-123	+2	200
AD-84	-7	180				ND-127	+2	200

REFERENCE DRAWINGS

PLAN OF GALLERIES AT EL 705	45-D-3137
FOUNDATION GROUTING BELOW EL 800	45-D-3138
FOUNDATION DRAINAGE BELOW EL 800	45-D-3139
FOUNDATION GROUTING AND DRAINAGE DETAILS	45-D-3140
INTERNAL DAM DRAINAGE SYSTEM	45-D-3141
LOWER DRAINAGE GALLERY	45-D-3142
LOWER DRAINAGE GALLERY DETAILS	45-D-3143
SUPPLEMENTAL GROUTING THRU FOUNDATION DRAINS	45-D-12993
FOUNDATION DRAINAGE AFTER COMPLETING SUPPLEMENTAL GROUTING	45-D-13566
RECORD OF GROUTING OF "A" LINE HOLES BY CONTRACTOR, 1934-1935	45-D-14155
ADDITIONAL FOUNDATION GROUTING USING ORIGINAL DRAINAGE HOLES	45-D-14156
RECORD OF DRAINAGE HOLES DRILLED BY CONTRACTOR IN 1935	45-D-14159

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
BOULDER CANYON PROJECT

BOULDER DAM

RECORD OF ADDITIONAL DRAINAGE HOLES
DRILLED BY GOVERNMENT FORCES 1942-8

DRAWN A.W.S. SUBMITTED A. W. Simonds
TRACED T.M. RECOMMENDED T. J. Fleming
CHECKED A.D.K. APPROVED W. H. Nalder
DENVER, COLORADO, MAR 10, 1948 | 45-D-14161

FIGURE 18

1939, which was 10 times that produced by the shallower original drains. As the grouting progressed, the flows diminished even though more drain holes were drilled. The original drain holes that were not used as grout holes were retained as drain holes.

Drains were also drilled in the roof of the highway tunnel, and drain holes were also drilled from tunnels Nos. 1 and 2 into the base of the highway tunnel. This drainage program dried up the highway tunnel.

Additional drains were also drilled in the Nevada abutment. The first series was drilled from the N-0 adit in an upstream direction into the area beneath the dam and between tunnels Nos. 1 and 2. A series of drains was also drilled from the Nevada pipe adit to drain the area carrying hot water which was thought to have originated in the fault zone crossing the Nevada abutment near the canyon wall valve house. Another series was drilled between tunnels Nos. 1 and 2 to intercept seepage appearing on the abutment behind the powerhouse walls.

On the Arizona abutment, drain holes were drilled from tunnel No. 3 and from Arizona No. 2 penstock tunnel to intercept wet areas in the contractor's adit between the left wing of the power house and visitor's platform in tunnel No. 3.

30. Summary of drilling and grouting. A summary of the drilling and grouting follows:

Year	Linear feet of hole drilled
1938-9	42,448.50
1940	48,298.60
1941	36,916.55
1942	31,974.60
1943	33,124.30
1944	26,451.50
1945	44,353.70
1946	25,971.75
1947	8,794.00
Total footage drilled	298,383.50

Summary of drilling:

Type of drilling	Linear feet of hole drilled
Grout holes	136,190.70
Redrill grout	115,852.90
Drain holes	34,115.05
Reaming holes	6,220.30
Miscellaneous drilling	6,004.55
Total	298,383.50

Year	Sacks of cement used
1939	4,605
1940	20,192
1941	22,815
1942	31,476
1943	43,043
1944	37,667
1945	34,953
1946	37,186
1947	19,178
Total for 9 years	251,115

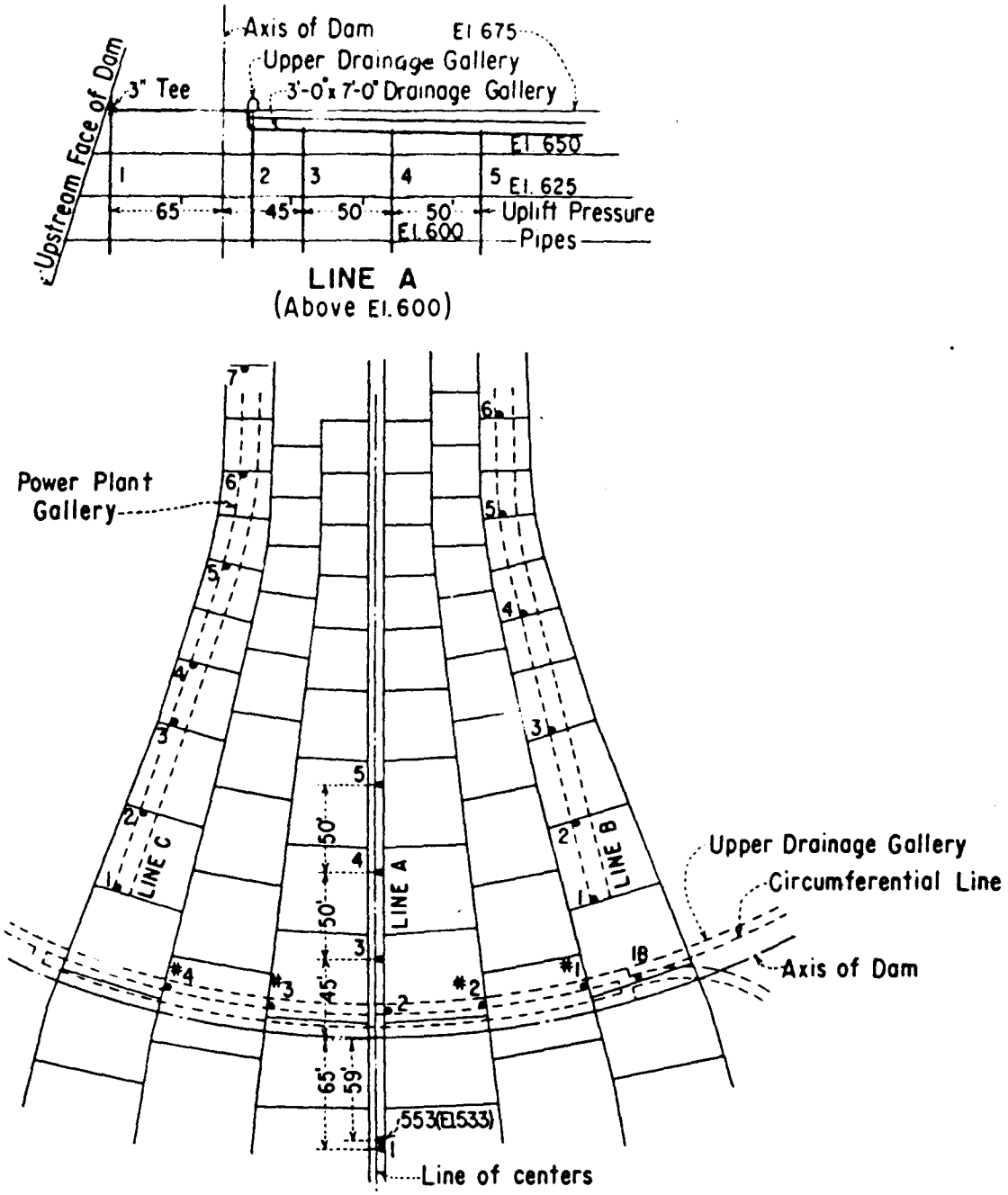
Area	Sacks of cement used
No. 1 Tunnel	37,316
No. 2 Tunnel	36,676
No. 3 Tunnel	52,360
No. 5 Tunnel	121
No. 1 Tunnel Adit	9,527
Arizona Abutment (New A Line)	42,561
Nevada Abutment (New A Line)	14,785
Nevada Spillway	57,769
Total sacks injected	251,115

VI. EFFECTIVENESS OF ORIGINAL AND ADDITIONAL GROUTING

31. Original grouting. Uplift pressures and leakage into the drainage galleries and penstock tunnels were excessive during initial filling operations in 1937 and 1938. Seepage also developed above the powerhouse on the Nevada side and at other points downstream. The increasing uplift pressure on the base of the structure particularly along sets B and C was of the greatest concern. The locations of the uplift pressure pipes are shown on figure 19 and the uplift pressures for September 30, 1938, are shown on figures 20 and 21.

Simonds[10] attributes the uplift to cold water from the normal percolation of reservoir water into the foundation and warm alkaline water coming from springs which apparently originated at a considerable depth beneath the surface. The following is quoted from his discussion:

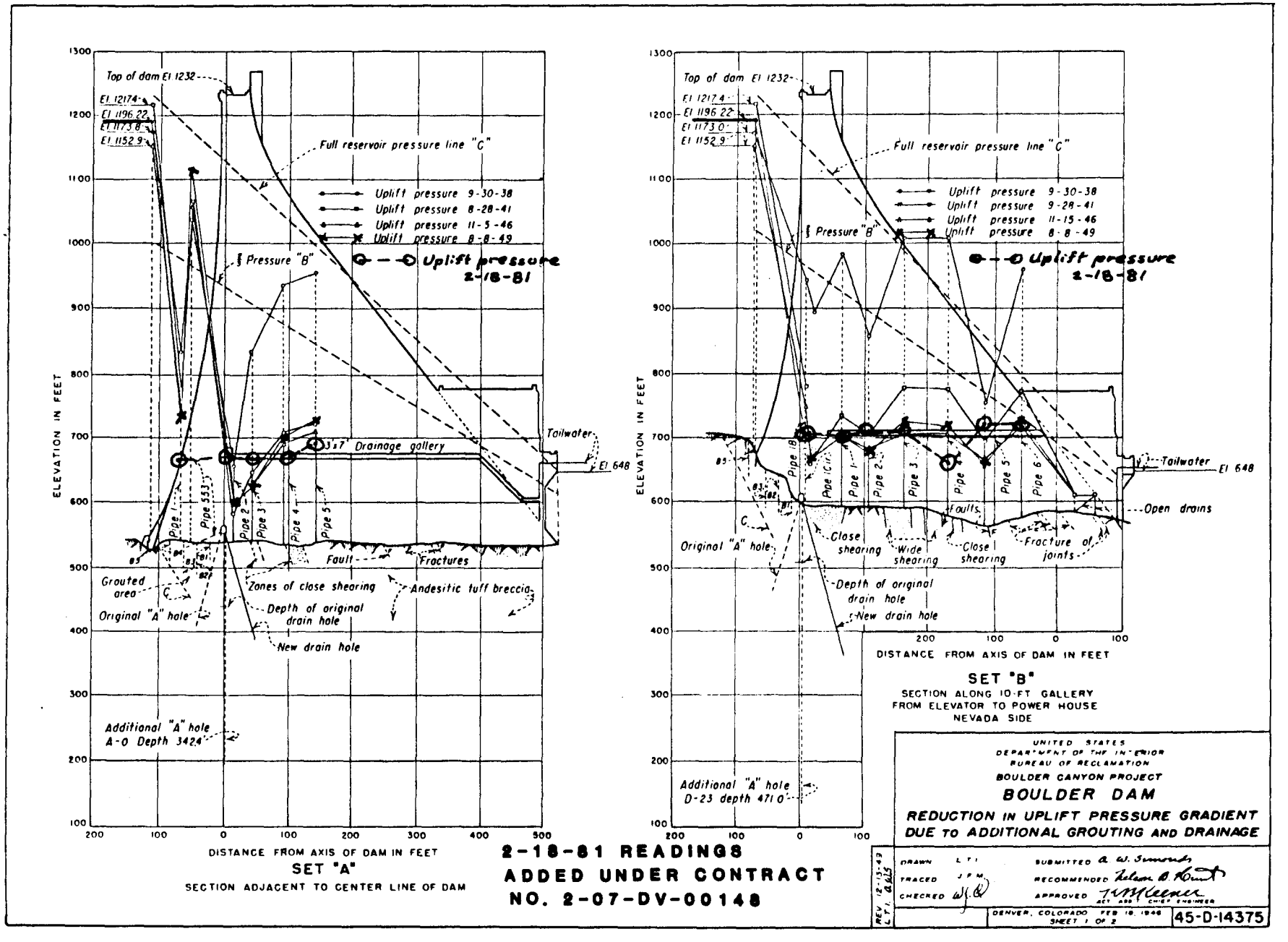
> "During the excavation of the foundation area, several warm springs were encountered along the Nevada side of the canyon. These springs were opened by drilling and pipe connections were made to them. The pipes were led into one of the lower galleries of the dam for grouting purposes after a sufficient cover of concrete in the dam had been placed over the areas from which the springs emerged. Other physical defects, in addition to the usual joints and cracks in the foundation rock, were several shear zones in the right central part of the foundation area. Some of these shear zones were in close proximity to the warm alkaline springs which occurred beneath the uplift pressure pipes in line B, Fig. 11.
>
> After sufficient concrete had been placed above the warm spring area, an attempt was made to grout the springs by pumping neat cement grout through the pipes previously installed for this purpose. When the cement grout came in contact with the warm alakline (sic) water, a flash set of cement occurred before the



LOCATION OF UPLIFT PRESSURE PIPES

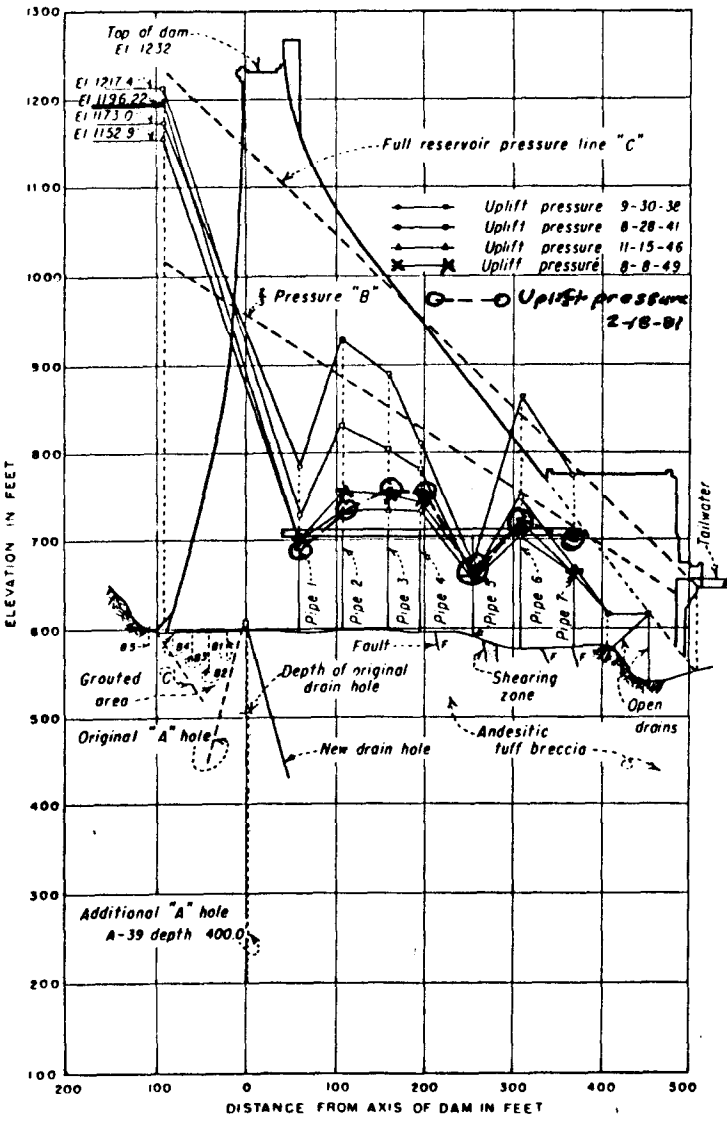
AFTER KEENER

FIGURE 19



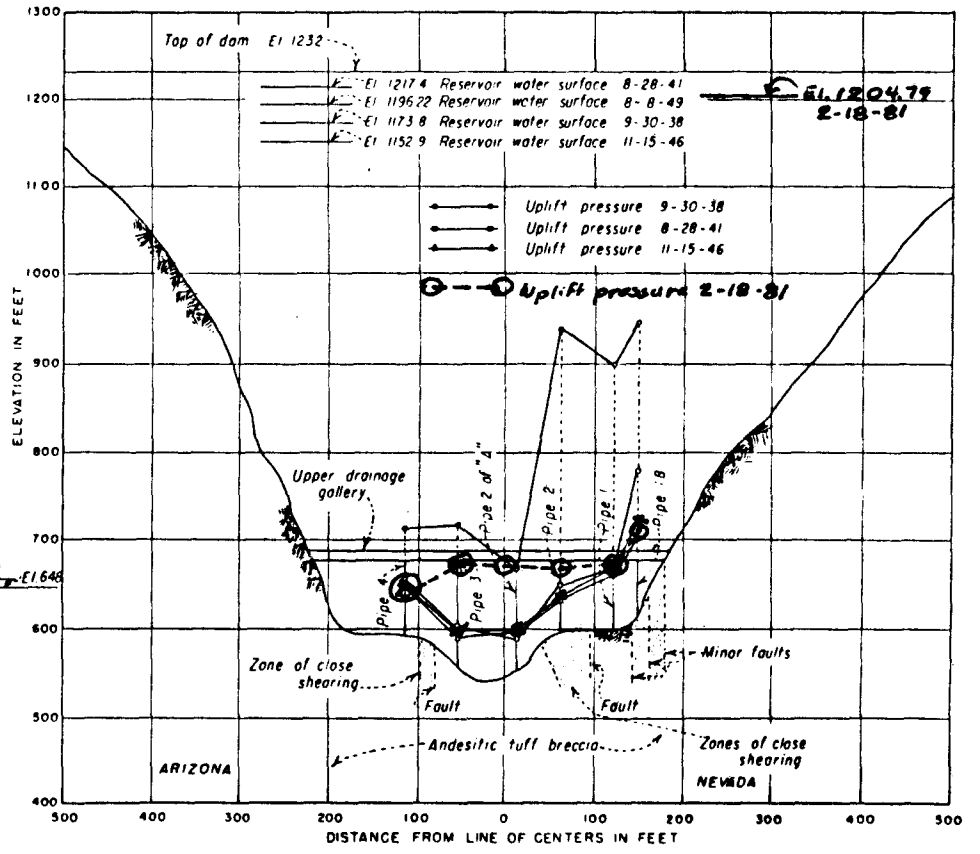
2-18-81 READINGS ADDED UNDER CONTRACT NO. 2-07-DV-00148

FIGURE 20



SET "C"

SECTION ALONG 10-FT GALLERY
FROM ELEVATOR TO POWER HOUSE
ARIZONA SIDE



CIRCUMFERENTIAL SET

DEVELOPED SECTION ALONG CENTER LINE
OF UPPER DRAINAGE GALLERY (APPROXIMATE)

2-18-81 READINGS
ADDED UNDER CONTRACT
NO. 2-07-DV-00148

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
BOULDER CANYON PROJECT

BOULDER DAM

REDUCTION IN UPLIFT PRESSURE GRADIENT DUE TO ADDITIONAL GROUTING AND DRAINAGE

DRAWN L.T.I. SUBMITTED A. W. Simonds
TRACED J.P.M. RECOMMENDED Nelson A. Conant
CHECKED APPROVED T. W. Kenny
ACT. ASS'T CHIEF ENGINEER
REV 12-13-49 L.T.I. R.E.S.
DENVER, COLORADO FEB 18, 1947 SHEET 2 OF 2
45-D-14376

FIGURE 21

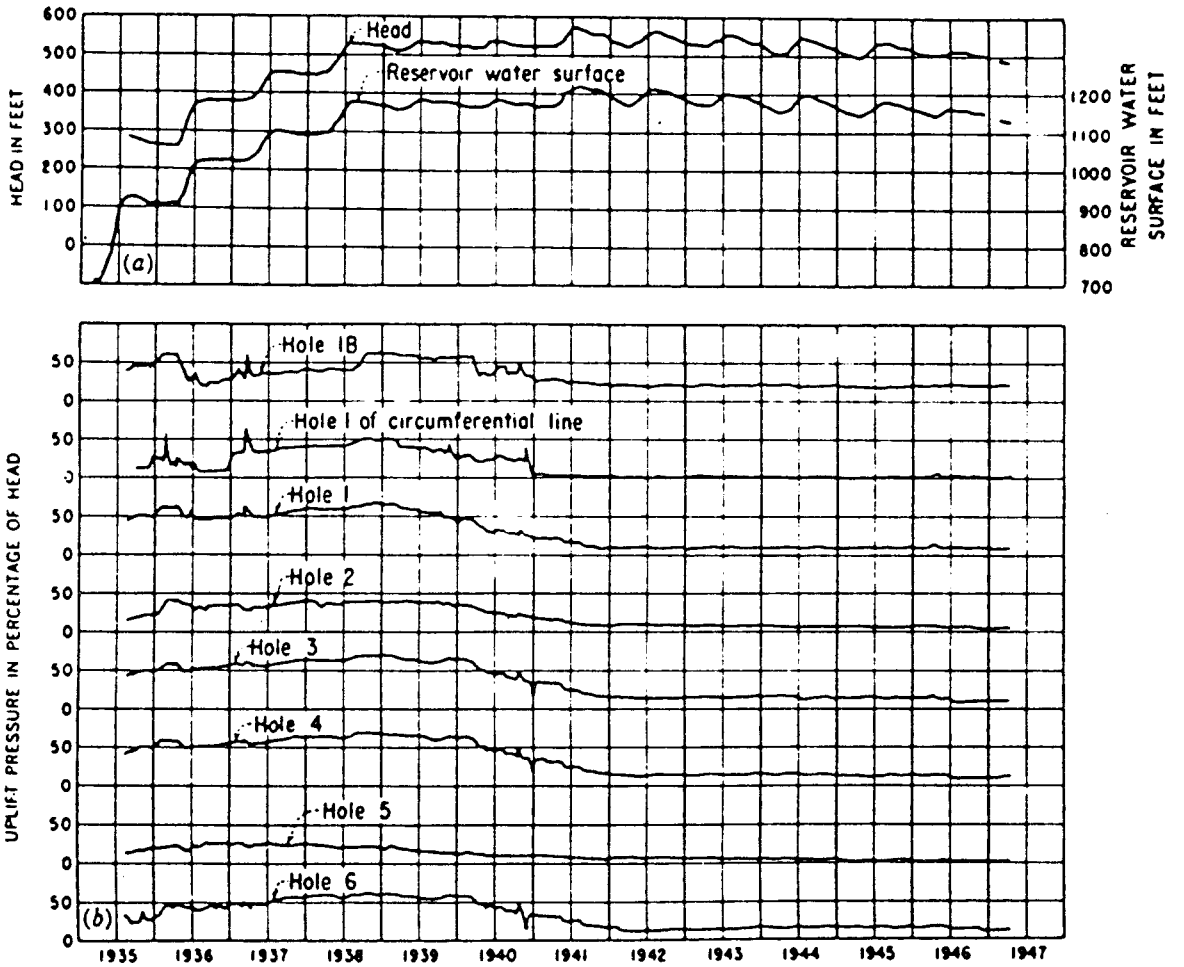
> springs could be grouted. This resulted in plugging the pipes that provided the only means of drainage from the warm spring area. The warm water subsequently found its way into the shear zone in the foundation area and caused the high uplift pressure in 1938 which was indicated by the installation along line B, Fig. 11. Subsequent grouting operations using special cements and retarders, and the drilling of foundation drains in strategic places reduced the magnitude of the uplift pressure until it was no longer excessive. It is interesting to note that on the Arizona side of the canyon, where there were no warm springs or shear zones, the uplift pressure along line C, Fig. 11, was much less than that which occurred along line B."

The figure 11 referred to in his discussion is the same as figure 19 of this report. The shear zones and faults found in the foundation and as plotted by F. A. Nickell in 1933 are shown on figure 11.

In the closure of their paper on grouting methods Simonds, Lippold and Keim(8) state, "At Hoover Dam it was found that the original grout curtain had not been deep enough to cut off the water under that extremely high head."

Apparently, the principals involved considered that the problems resulted from a blockage of drainage from the warm springs and inadequate depth of the grout curtain.

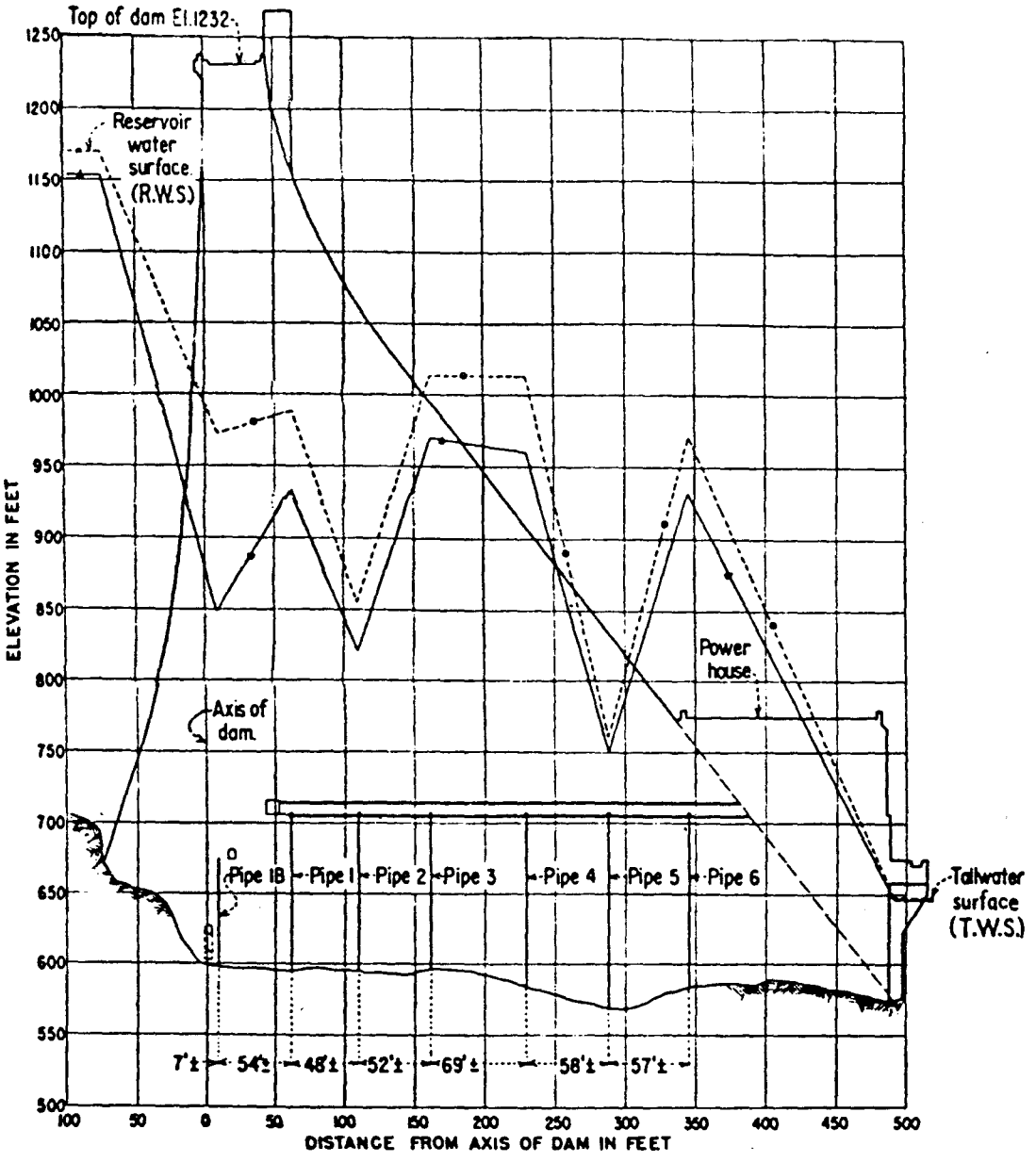
Figures 22 and 23 were reproduced with ASCE's permission from figures 12 and 13 of Keener's(11) paper on uplift pressures. These plots are extremely valuable because they indicated even during the early stages of filling that all holes along line B had relatively high readings in percentage of head. Of particular concern were readings for holes 3 and 4 which were located 161 feet and 230 feet, respectively, downstream from the dam axis; and of even more concern was the readings from hole 6 which was



UPLIFT PRESSURES AT BASE, LINE B

after Keener

FIGURE 22



DATE	R.W.S. EL.	EL OR EQUIVALENT EL OF W.S. IN PIPE							T.W.S. EL.	LEGEND
		1B	1	2	3	4	5	6		
JAN. 14, 1938	1095.33	822.05	909.78	825.67	933.92	938.00	757.06	906.18	645.47	
FEB. 15,	1094.65	821.05	904.78	821.67	930.92	935.00	750.06	909.18	645.60	
MAR. 15,	1099.15	814.05	909.78	819.67	934.92	937.00	750.06	911.18	645.05	
APR. 15,	1100.75	836.05	909.78	819.67	938.92	940.00	749.06	915.18	646.75	
MAY 13,	1119.90	838.05	918.78	819.67	944.92	948.00	750.06	922.18	645.55	
JUNE 15, 1938	1152.93	848.05	933.78	819.67	970.92	960.00	750.06	932.18	645.70	—•—
JULY 15,	1172.59	853.05	957.78	843.67	983.92	987.00	760.06	953.18	646.06	
AUG. 15,	1172.85	859.05	974.78	856.67	1000.92	999.00	761.06	966.18	645.95	
SEPT. 15,	1173.03	890.05	978.78	857.67	1006.92	1007.00	763.06	970.18	646.40	
OCT. 14,	1172.81	978.05	987.78	855.67	1008.92	1013.00	766.06	977.18	647.00	
NOV. 14, 1938	1169.19	972.05	988.78	854.67	1013.92	1014.00	761.06	971.18	647.12	--o--
DEC. 16, 1938	1168.37	972.05	987.78	854.67	1007.92	1010.00	755.06	966.18	646.84	

LINE B ALONG 10-FOOT GALLERY FROM
ELEVATOR TO POWER HOUSE-NEVADA SIDE

UPLIFT PRESSURES AT FOUNDATION, LINE B

(MEASUREMENTS DURING 1938)

after Keener

FIGURE 23

located 345 feet downstream of the axis and only about 145 feet from the projected downstream toe of the dam. As the grout curtain and drainage curtain were located at the axis of the dam, it was evident from the filling data even in 1935 and 1936 that seepage and seepage pressures were passing through or around the grout and drainage curtains.

Set A only extended about 150 feet downstream of the axis. Pipe 5 in set A had a reading of El. 952 on September 30, 1938, which represented an intermediate reading between pipes in sets B and C at this location. If additional pipes in set A had been located further downstream in the drainage gallery, it must be assumed that the readings would have been similar to those found in sets B and C.

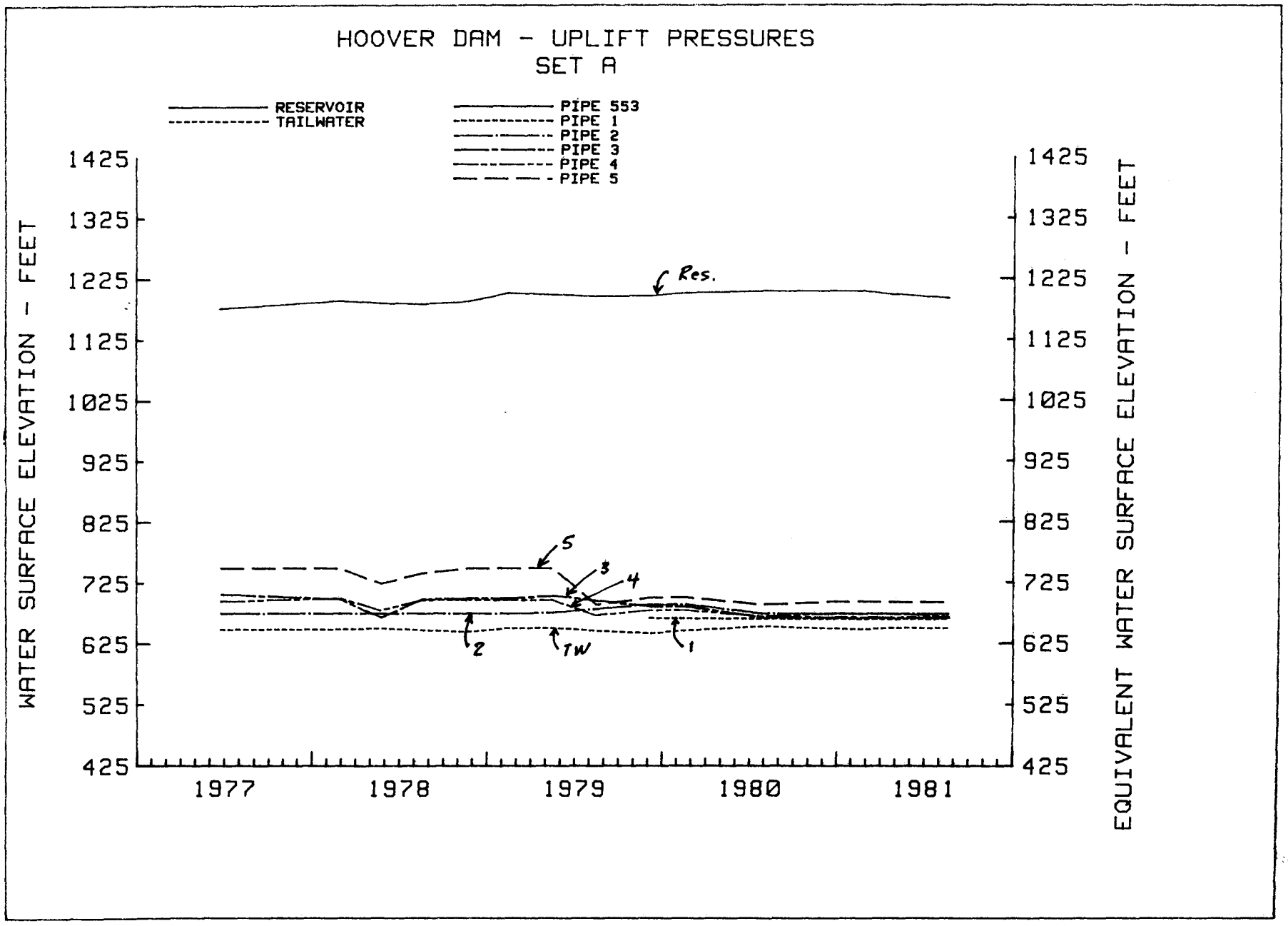
The reading for pipe 6 of set B for October 14, 1938, with a headwater of El. 1,172.8 was El. 975 which was about 200 feet above the face of the dam and 400 feet above the base of the dam. Although the pipes represent point readings, it must be assumed from a dam safety standpoint that the uplift extended over most of the downstream area. If the reservoir had risen to the top of the spillway crest El. 1,205.4 before corrective action was taken, the downstream toe of the dam would have been subjected to an even greater uplift. Hence, it was most fortunate that considerable corrective action had been taken before the reservoir rose to El. 1,220.45 on July 31, 1941.

32. Additional grouting. The first order of business was to drill a series of drain holes beneath the downstream toe of the dam. Drilling of drain holes from the powerhouse gallery, central

section, El. 616, was started in October, 1938. Drilling of the 15 drain holes from the powerhouse gallery resulted in flow from all holes when they penetrated the bedrock. Warm water under pressure was struck in holes S-11 and S-15; the flow decreased rapidly and in a few weeks diminished to a small flow. The uplift pressure readings for 1938 through 1943 are shown in table 1. The readings of January 9, 1939, are assumed to reflect the effects of drilling the powerhouse drain holes. On line C, readings for C6 and C7 are greatly reduced from the previous reading of October 14, 1938. On line B, the reading for B6, a critical location, is not materially reduced; but the reading for B5 shows about a 20% reduction from the previous reading. Readings for 3A, 4A and 5A show no appreciable reduction. The reduction in pressures along line C were achieved with drains that only penetrated five feet into rock beneath the dam. Nevertheless, additional work in the form of grouting was needed to further reduce the uplift and seepage problems.

A review of table 1 indicates that much of the reduction in uplift was accomplished in 1939, 1940 and 1941 by a combination of grouting and drainage. These reductions are shown on the plots for September 28, 1941, on figures 20 and 21. Although some further reduction in the uplift pressures was accomplished after 1941, the work primarily reduced the amount of seepage which was in itself very important.

33. Current status of uplift pressures and seepage. The uplift pressures for February 18, 1981 are plotted on figures 20 and 21. The reservoir water surface on February 18, 1981 was at



Header file 7HOUPA

FIGURE 24

ENGINEERING & RESEARCH CENTER - STRUCTURAL BEHAVIOR SECTION

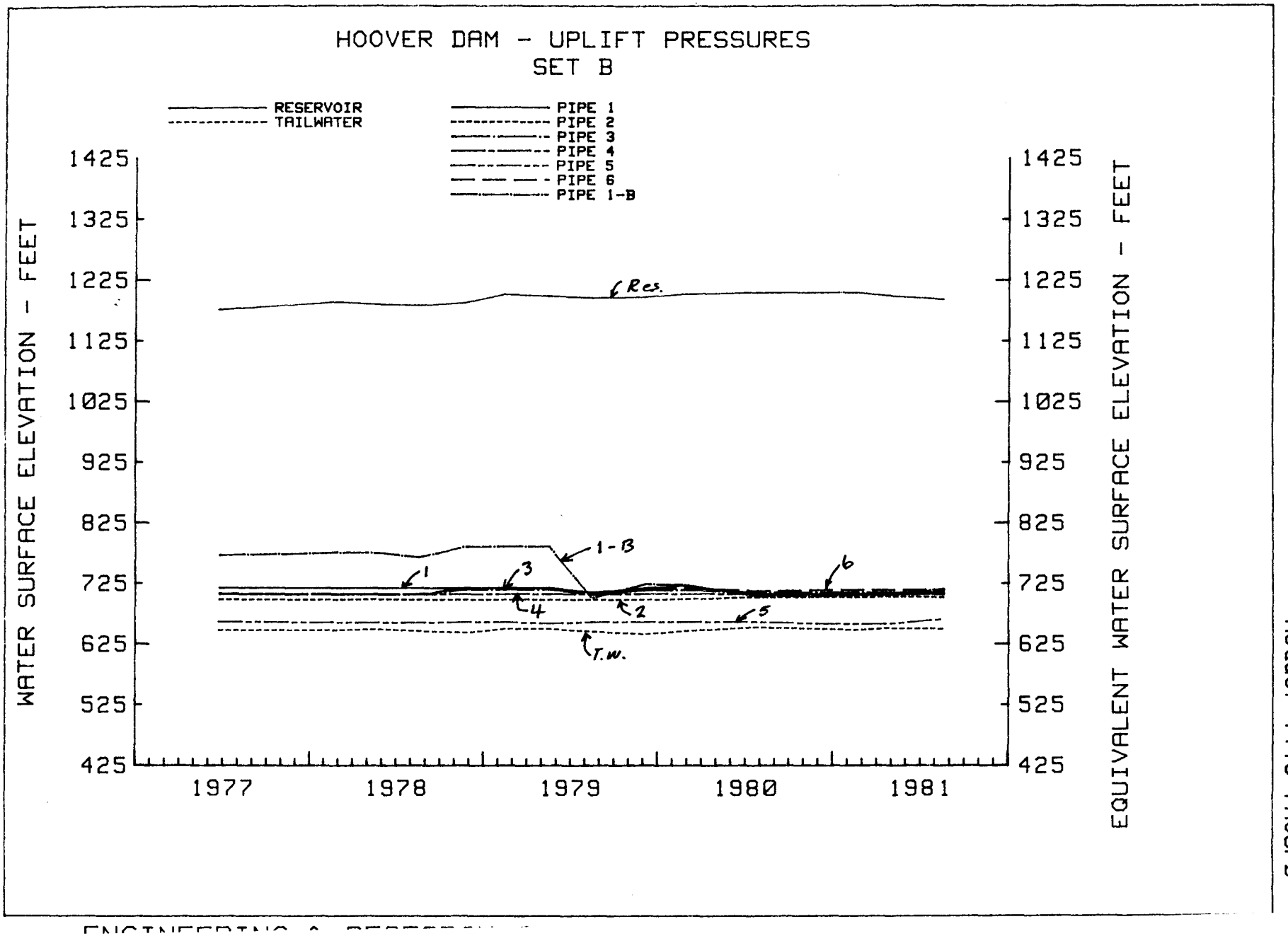


FIGURE 25

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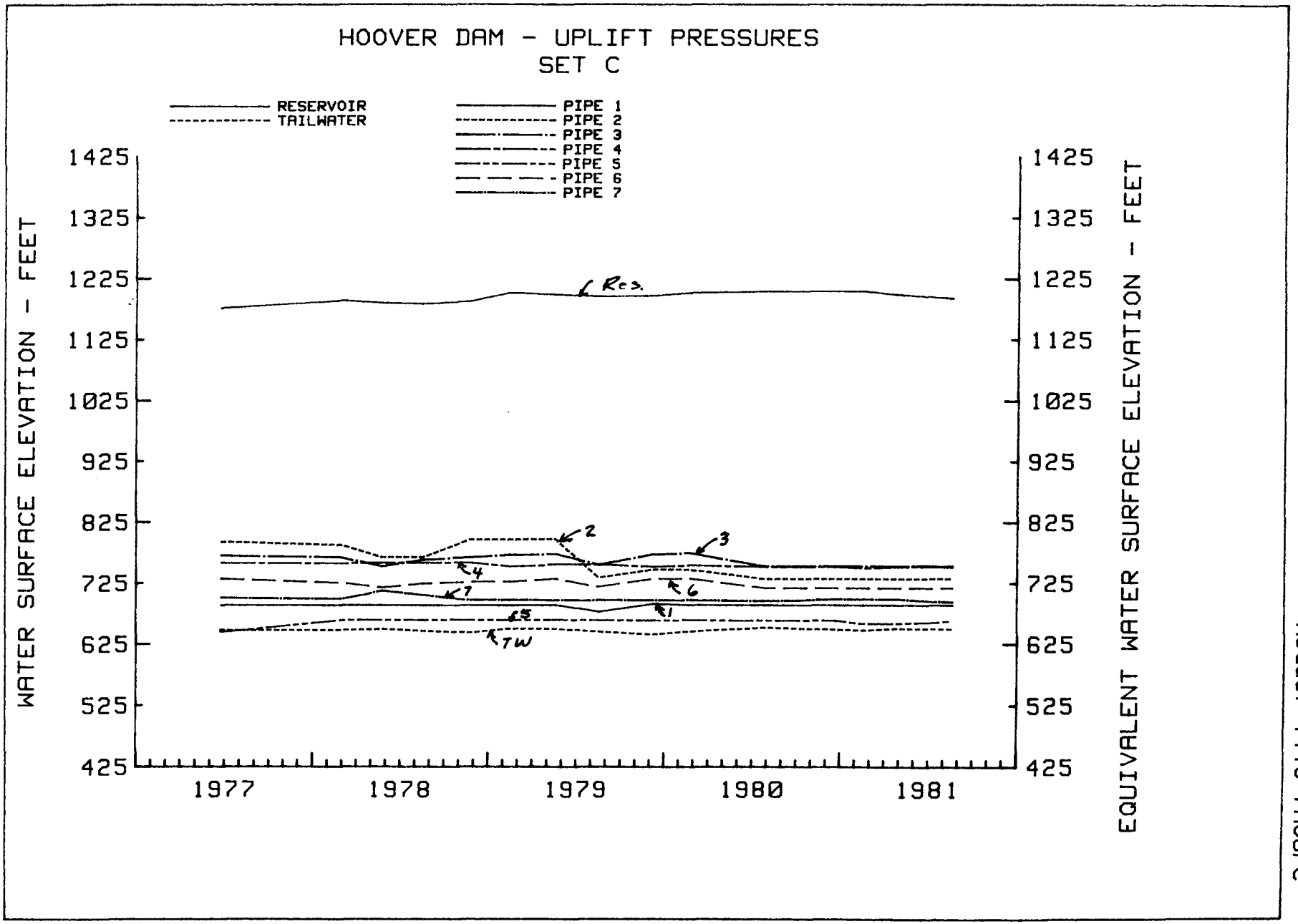


FIGURE 26

Header file 7HOUPC

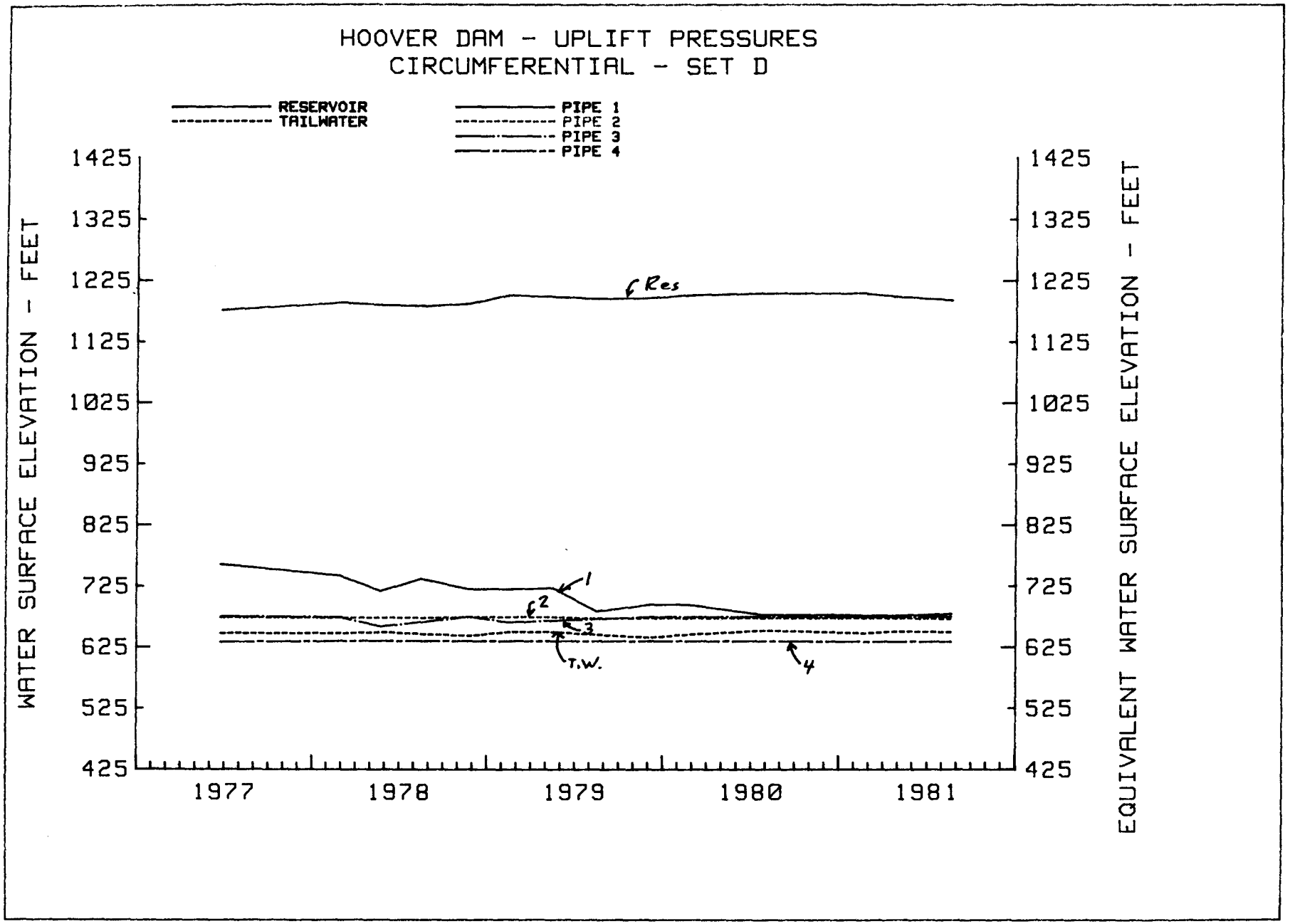


FIGURE 27

ENGINEERING & RESEARCH CENTER - STRUCTURAL BEHAVIOR SECTION

Header file 7HOUPD

at El. 1,196 was 135 gpm. The SEED inspection team found in January and February, 1979, that the seepage in the foundation galleries was about 100 gpm, which includes seepage from internal drains within the concrete. The SEED team indicated that many of the foundation drains had either no flow or only discharged a trickle of water. Data on the seepage since the drains were cleaned with high-powered jets in 1979 are not available.

The SEED team stated that:

> "Seepage was reported as about 100 gal/min in the foundation galleries, 700 gal/min in the Nevada lower penstock tunnel, 200 gal/min in the Arizona lower penstock tunnel, 200 gal/min in the Nevada spillway drainage tunnel. Only minor leakage was occurring in the upper penstock tunnels. Considerable leakage was observed in the downstream, essentially horizontal portion of the Nevada spillway tunnel but no information was available on the volume."

Simonds and Boggess[6] reported that at the end of the additional grouting the flow from tunnel No. 2 was 1,100 gpm, the flow from tunnel No. 3 was 144 gpm, and that part of the Nevada spillway drainage tunnel was dry. The amount of seepage in the other areas was not reported.

From the available data, it can be concluded that additional grouting is not needed at this time to reduce the seepage from the foundation drains or to reduce the foundation uplift pressures; however, continued maintenance and cleaning of drain holes is necessary for the safety of the dam. The need for additional grouting to reduce seepage into the tunnels cannot be determined from the available data.

VII. ANALYSIS

34. Pre-construction geologic investigations. Geologic investigations completed prior to construction consisted of: (1) a report[12] based on field work by F. L. Ransome and H.A.C. Jenison of the United States Geological Survey in 1922; (2) a report submitted by H.A.C. Jenison in 1923 entitled "Geology of Spillway Basin at Lower "D" damsite in Black Canyon"; (3) a short report dated February 14, 1931, by F. L. Ransome (then a consulting geologist) on drill cores and spillway sites; (4) drilling of 39 vertical holes in the river channel; and (5) drilling of 2 horizontal holes in the abutments.

In addition to geologic information developed by the Bureau's staff and by consultant F. L. Ransome, advice was also available from Dr. Charles P. Berkey, an eminent engineering geologist and a member of the Colorado River Board.

As the 2 horizontal holes were drilled during the bidding period (Dec. 15, 1930 - Mar. 4, 1931), the assessment of the geologic conditions within the abutments was based on surface mapping of the near-vertical cliffs and the tops of the abutments. Only 1 hole in the river bottom penetrated the rock more than 50 feet. Hence, at the time of the bidding, there was very little information available relating to the character and condition of the rock at depth in the valley bottom and in the abutments. In particular, there was little if any information on open jointing, open seams, and other rock defects that could transmit seepage after impoundment of the reservoir. In areas of igneous rocks, the possibilities for unexpected conditions not revealed by

surface mapping are extremely great as the different lava flows produce unpredictable subsurface conditions. Detailed information on the subsurface conditions to the depth and width of the zone influenced by the reservoir impoundment was critically needed in the design of the grouting and drainage systems; and as this information was not available for the designers, it must be concluded that pre-construction geologic investigations were inadequate.

35. Original grout lines and drain holes. (a) Design. The design was based largely upon experience and precedence in the foundation treatment for a number of masonry dams which were not comparable in size to Hoover Dam. The depth of the grout curtain under the maximum section was 150 feet which was equivalent to 21% of the structural height of the dam. The maximum depth of the drain holes was about 100 feet. No major changes were made in the design of the grout lines and drain holes as a result of the information obtained during construction. Excessive seepage quantities and excessive uplift pressures developed during the initial filling indicating that the design was inadequate. The design of the grout lines and drainage system should have been based on an analysis of the geologic conditions and on a study of the anticipated seepage flow paths from the maximum reservoir level. No ratio of depth of grout curtain to height of dam is considered logical as each site has its own unique conditions. One site may need a deep grout curtain in the valley bottom whereas another site may need a grout curtain penetrating to a great distance into the abutments.

It is considered that the "C" line should have been drilled and grouted prior to the "A" line as this would have

provided additional filling of the shallow rock defects before commencement of the deeper grouting. By starting the "A" line later additional concrete would have been in place to resist the high grout pressures used.

(b) Specifications. The specifications contained very little information pertaining to the geology and foundation conditions at the site. The seven drawings showing logs and profiles of 39 holes drilled along lines upstream and downstream from the axis defined the top of rock in the river channel, but did not indicate the percent of core recovery or characteristics of the bedrock. A drilling and grouting contractor would have been bidding "blind" without information pertaining to water losses in drilling and pressure testing and the nature of the imperfections in the rock, i.e. faults, joints, etc.

The specifications required pressure washing of all holes before grouting was begun. However, they did not require washing at maximum-pump capacity or that washing should continue until the water clears or for any specified period of time. If there was no drill water return, the pump should have been run at maximum capacity for a period of approximately five minutes to clear the opening and lubricate the hole prior to grouting.

In addition, the specifications have no provisions for water testing holes for a specific period of time, or for caulking grout leaks. The capacity of the grout pump in gallons per minute, type of water meter and pressure gage, the inside diameter of grout supply lines and the necessity for, and method used in backfilling grout holes was not covered in the specifications. The specifications did not give the sequence of drilling and grouting or indicate the order in which holes were to be drilled and grouted.

(c) Drilling. The specifications required the minimum diameter of each hole at the bottom to be not less than one inch. Notwithstanding the fact that a fairly large number of grout jobs have been successfuly completed using small diameter holes, it is considered that there is sufficient advantage in drilling larger diameter grout holes, i.e. BX (2-5/16") and AX (2-15/16") to justify their use. Advantages in the use of the larger diameter holes are as follows:

(1) The angle and orientation can be better maintained in deep holes because the rods are heavier and more rigid in the drill string than the slim flexible string of rods used in small diameter holes. This tends to keep the bit from wandering off course. In some cases it is necessary to add "drill collars" or stabilizers to the string of rods to reduce rod whip and to maintain a relatively straight hole.

(2) There is little need in specifying a 1-1/2-inch grout supply line if the diameter of the hole is much less than 1-1/2 inches. At every restriction in the supply line to the hole, grout tends to build up and eventually will cause the hole to plug off. In addition, if a hole is taking grout, every restriction in the grout supply line or the hole results in loss of pressure due to friction and back-pressure buildup which is reflected at the header gage.

The consolidation or "B" grout holes were drilled by the percussion method. This method is normally not considered good practice because circulated cuttings and dust tent to fill openings which might ordinarily have accepted grout. However, it

is considered that percussion drilling of shallow holes in hard rock or rotary drilling using air as a circulating medium is acceptable if the holes are thoroughly cleaned on completion of drilling.

(d) Water-pressure tests. The term pressure washing is assumed to be the same operation which is ordinarily considered to be pressure washing and testing on most jobs. However, at Boulder Dam it was different in that the flow of water into the hole was not metered and the duration of the operation was based on what Minear[7] called "any noticeable pickup or increase in pump speed." This would suggest that the rate of water take in gallons per minute was not utilized as a guide for determining the proper water-cement ratio to use in starting the grouting.

(e) Grout mixes. The formula used at Boulder dam for starting mixes worked well because of the extremely high pressures used in all lines of holes. The rule insures starting a hole with a thin mix, which may at times not be necessary or even practical. For example, a blanket hole requiring a minimum of pressure of 300 p.s.i. would be started with a 3:1 mix. If the hole had a pressure test water take of say 60-70 gpm, it would be more practical to start grouting with a 1:1 or even thicker mix. If the water take was only 3-5 gpm, the starting mix (3:1 water-cement ratio) by the Boulder rule would probably be too thick. The starting mix should be based on the results of the water take in pressure tests.

With the exception of sand, no additives to grout were specified and records do not indicate that sand was used in the

operations. Minear[7] stated that "only neat cement grout should be used." Experience has shown that fine-graded sand can be used successfully in grouting holes that accept grout freely with little or no pressure build-up. Use of a fluidifier in sanded mixes helps keep the sand in suspension. Sand should not be used in holes that take grout slowly or have any appreciable pressure build-up.

(f) Grout-injection pressures. A comparison of the maximum pressures used in the A-holes and the pressures determined from the design formula is presented in the following tabulation:

Elevation Collar of Hole	Reservoir Head Pressure at Collar of Hole*	Maximum Pressure by Design (Res. Head + 50 p.s.i.)	Actual Max. Pressures Used
Feet	p.s.i.	p.s.i.	p.s.i.
1200	12.5	62.5	300-400
1000	98.5	148.5	750
800	184.5	234.5	750
552**	291.1	341.1	1000

*Reservoir head elevation based on top of flood pool elevation 1229
**Lower gallery floor elevation

In all cases the pressures used were higher than the designers had established in the specifications. Although the rock was reportedly hard, and essentially free of significant planes of stratification, it was highly jointed and occasionally broken by shear zones. Grout injected into such fractures under very high pressures could result in damage to the foundation rock as well as to the concrete structure.

The pressures used should have been the minimum amount of pressure needed to make the grout flow, and the maximum pressures used should have been based on the computed safe pressure at the

point of application. The computed safe pressure is based on the weight and/or strength of rock available to resist the uplift and splitting pressure of the grout at the point of application. For example the "B" holes were grouted in a single stage from a 1-1/2-inch diameter nipple set approximately four feet into rock. Consequently, safe injection pressures would have been more on the order of 4-5 p.s.i. at the collar instead of the 300-400 p.s.i. used.

The pressure due to the static load of the column of grout in the hole, apparently was not taken into consideration in determining the rules governing pressure at Boulder Dam. This, plus the fact that the "A" and "C" holes were grouted full stage from the pipe nipple added to the danger of rupture or lifting of the rock or dam.

In addition, it would have been better to have delayed the high-pressure grouting until essentially all of the concrete had been placed.

(g) Spacing of holes and closure. For the "B" line grouting the contract drawings showed five lines of "B" holes but only three lines were drilled and grouted. In addition, the second and third lines were only partially completed.

The unit takes are shown in the tabulation on page 29. The unit takes on the Nevada side do not show a progressive decrease in unit take from the primary to the tertiary line. This may indicate that lifting or excessive surface leakage occurred in grouting the center line. The unit take when grouting was discontinued was 0.728 sacks per linear foot of hole. Grouting should have been continued until the line was tightened.

The progressive reduction of unit take from 1.243 to 0.188 on the Arizona side indicates the grouting was effective.

Minear[7] indicated that the "C" line grouting was not effective as a cut-off within itself due to leakage in and beneath the fillet, leaks in the "A" gallery, leaks into the abutment grouting system and leaks from the abutment rocks that had not been sealed by "B" line grouting. One could only agree with his remark that "high pressure caused transverse cracks to open up in the fillet due either to uplift or tension within the concrete". This is especially true when pressures of up to 750 p.s.i. at the collar were used in grouting the holes.

On the "A" line, split spacing of grout holes should have been continued until the curtain was tight. This should have been done even if it required construction of an auxiliary line from the floor of the gallery.

Lower grout pressures and somewhat thicker grout should have been used when it became apparent that grout was leaking into the abutment contact grouting system and to the surface.

Grout holes should have not been abandoned because of excessive take. The excessive take indicated there was a void in the rock that needed to be sealed to prevent seepage. Thicker mixes and possibly lower pressures should have been used until the holes refused. Where holes were abandoned due to leakage at the abutment contact, the holes should have been redrilled and regrouted after the contact grouting was completed. Research should have been done on how to prevent flash set in the warm water areas. All abandoned holes represented potential leakage paths.

Descending-stage grouting rather than single-stage grouting should have been used in constructing the curtain, especially because of the extremely high-injection pressures used. Note, packers had not been developed for high pressures at that time.

(h) Refusal criteria. The criteria specified for refusal is practical. To continue grouting after a hole refuses to take one cubic foot of grout in 10 minutes not only works a hardship on the contractor but is in no way a benefit to the government.

As previously noted some holes were abandoned before refusal was reached.

(i) Backfill methods. It is difficult to understand how a hole that was completed with a grout mix thinner than 1:1 would not develop voids as the thin grout set. The specifications should have required sounding of all completed grout holes and backfilling with a thick grout.

(j) Foundation drains. The foundation drains were installed on 10-foot centers between axis Stations 5+16 and 8+04 instead of 5-foot centers specified. This section was across the canyon bottom. There is no record that excessive flows from individual drains was occurring; hence, the drilling of alternate drains in this section of the dam to depths of 100 feet probably did not adversely affect the uplift pressures. The problem was that neither the grout curtain nor the drain holes penetrated deep enough into the rock in the canyon bottom or into the abutments to intercept voids in the rock carrying reservoir water under high pressure. In volcanic formations, voids due to different lava

flows and fissures due to vents may be expected in erratic patterns. Under these conditions, bypassing of a shallow drainage curtain located about 75 feet from the upstream face of the dam and causing uplift at the downstream toe (575 feet downstream) should be expected. Hence, another line of drainage holes along the downstream toe would have helped relieve the excessive uplift pressures.

36. Additional grouting 1938-1947. (a) General. In comparing the original grouting and the additional grouting there are many differences:

(1) The original program followed a more or less set pattern for location and depth of the grout and drain holes; whereas, the additional program permitted considerable flexibility. As the additional program was accomplished by government crews and equipment, changes presented no contractual problems which was a distinct advantage.

(2) The original grouting program evidently did not include exploratory holes to supplement the limited information available from the design-stage drilling and a limited amount of drilling completed after construction started; whereas, exploratory cored holes were used extensively in the additional program which gave the supervisors considerably more information on which to base decisions.

(3) The original program was completed under no pool or in the later stages where the pool was lagging the grouting and drain work; whereas, the additional program was completed under relatively high pool stages. Under the latter condition there was

the disadvantage of working against high-water pressures in the holes, but there was an advantage in that the results of the work could be checked against seepage conditions and against the uplift gage readings.

High-pressure grouting was in its infancy when the original grouting was accomplished, and the equipment and methods had been better developed when the additional grouting was accomplished. Nevertheless, the engineers and grouting personnel in the additional program are to be commended for the ingenuity shown in meeting and solving drilling and grouting problems and in adjusting their program to achieve the intended results.

(b) Water-cement ratios. The water-cement ratios were higher in the additional grouting program than in the original program. It is understood from the interview with Fred Lippold that O. E. Boggess was transferred to Hoover Dam from Grand Coulee Dam in 1939. At Grand Coulee Dam, Boggess had used grout mixes in the range of 2:1 to 1:1, but it is understood that he found that higher water-cement ratios were needed at Hoover Dam to obtain acceptance in many holes. According to Simonds and Boggess' report[6] "It was learned by experience that grout having a water-cement ratio thicker than 3:1 by volume could not be injected at pressures greater than 450 p.s.i. without risking the plugging of the hole being grouted. A review of the grout records of individual holes seemed to indicate that thinner grout mixes were more successful for squeezing off seepage through the andesitic rock." "Thin grout mixes injected at pressures of 500 pounds per square inch or slightly greater formed excellent films of grout.

This was observed from cores drilled subsequently from nearby holes."

It is understood from the interview with Fred Lippold that when thin-mix grout (at the pump) broke out in the tunnels it had the consistency of a 2:1 mix. This observation indicates that possibly some of the water in the mix bled off in the finer rock fractures leaving a thicker mix travelling through the wider fractures to the point of break out in the tunnels.

Boggess[13] states in reference to hole A-124:

> "The author mentions hole A-124 in the Arizona abutment that accepted a total of 8,258 sacks. This hole was started with a w/c of 10:1. During the injection of the first 100 sacks the w/c was gradually reduced to 6:1. Several attempts were made to reduce the w/c to 5:1 as the grouting progressed, but each time the hole showed signs of tightening up and the w/c was changed back to 6:1. The grouting of this hole had a widespread effect in drying up the Arizona abutment, particularly in the upper penstock tunnel."

As Boggess was the field engineer in charge of the additional grouting, it must be concluded that the thin grouts used were necessary.

(c) Grouting pressures. The injection pressures used in the regrouting were essentially the same as those used in the original grouting. The dam was to full height. Both single-stage and descending-stage grouting methods were used. However, even under these conditions it may have been possible to lift the dam and/or the rock with the high pressures used, but there are no available records on vertical movements to determine if jacking occurred. Some of the transverse movements of the dam recorded by Peterson[14] may have been caused by the grouting pressures.

In some of the examples presented by Simonds and Boggess[6] questions can be raised as to the need for high pressures. In the grouting of stage 1 of hole A-124 a leak developed in the roadway east of the dam and the hole was sealed off with 1:1 grout at a pressure of 550 p.s.i. Hole A-124 is a slightly inclined hole located at approximate El. 1,000. See figure 12. The roadway was near El. 1,232 which meant the grout had to be raised approximately 232 feet. The question is: "If you are trying to create a grout barrier even for the full width of the dam, is it necessary to have enough pressure to raise the grout 232 feet in elevation?"

(d) Spacing and closure. The records available for review do not include data showing the take per hole and per foot for the primary and intermediate holes; hence there is insufficient information to comment on the statistics involved in th closure criteria. The final results achieved in reducing seepage quantities and uplift pressures indicate that the criteria used in the closure were satisfactory.

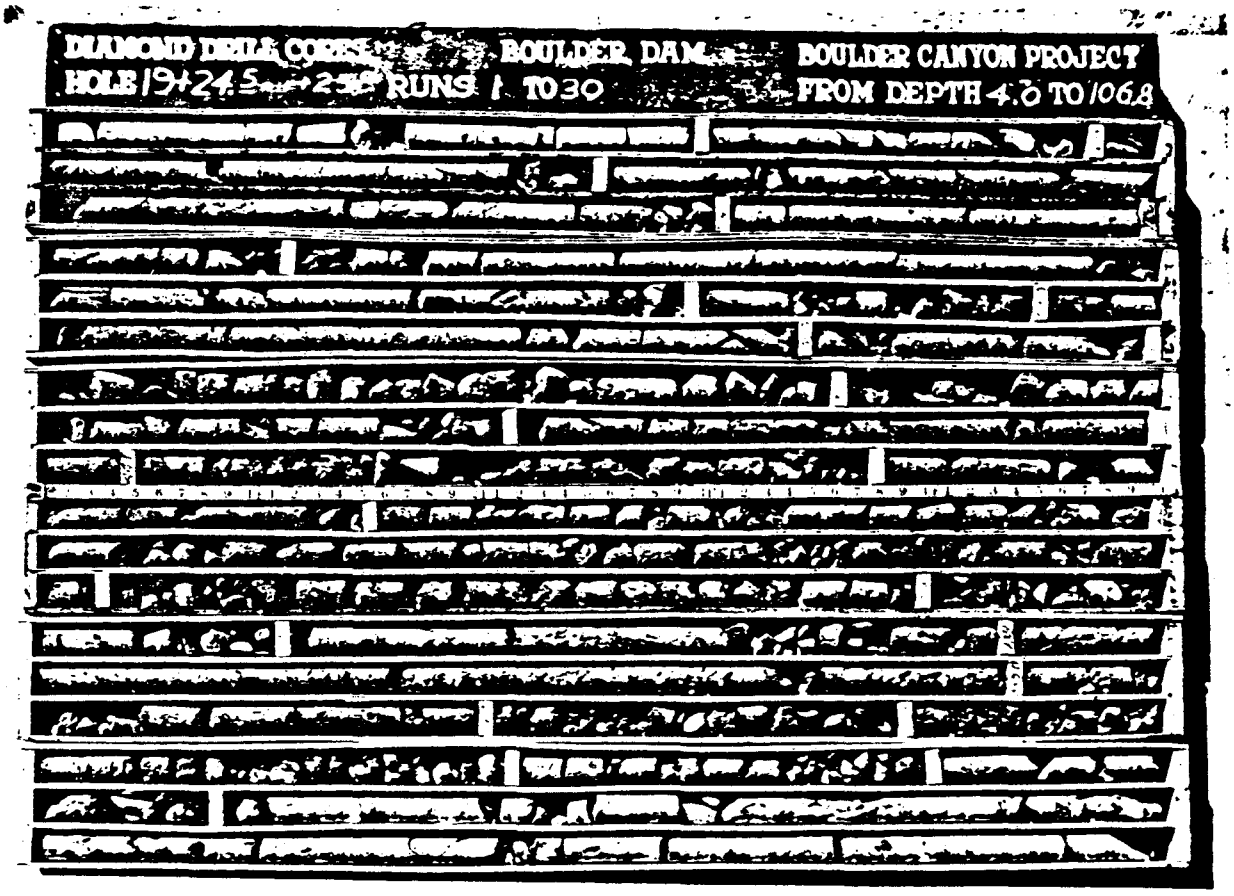
(e) Drain holes. The deeper drains drilled in the additional work were adequate to relieve the excessive uplift pressures. If the drains drilled from the powerhouse in 1938 had been drilled deeper into rock they may have been more effective in relieving the uplift pressure at the downstream toe of the dam.

37. Unexpected geologic conditions discovered during grouting. During the original grouting the unexpected geologic conditions encountered were the warm springs, which inhibited grouting, and the high grout takes on the Nevada abutment. The drilling during

the initial construction stage of flat angle hole D-56-E-49 into the Arizona abutment at El. 687.4 and of flat angle hole D-130-2W at El. 748 in the Nevada abutment located many unexpected soft and broken zones, mud seams, and basalt.

During the additional grouting, large water flows under high pressure were encountered unexpectedly in many holes. Mud seams, sand seams, soft and broken zones were found in many holes. Open seams which took up to 1,500 sacks of cement before any back pressure developed in the hole were encountered in the Arizona abutment. Grout break outs were encountered in the tunnels and roadway on the Arizona abutment indicating a vertical grout travel of over 550 feet and a horizontal travel of several hundred feet in the Arizona abutment. Hydraulic connections were found between a shear zone in hole D-23 at El. 200 and water appearing on the Nevada abutment between El. 830 and El. 940. Fluorescein dye introduced into D-100, a horizontal hole at approximate El. 910 appeared in the return flow of holes A-1 and D-1 located in the El. 553 gallery beyond D-23.

Extensive voids and areas of poor rock with high water flows were also found in the Nevada abutment. For instance, an exploratory hole drilled from Station 19+24.5 in tunnel No. 2 on the Nevada side (see figure 14) at an upward angle of 25° had poor and broken rock from a depth of 8 feet to 107 feet as shown on figure 27. The collar of this hole is located near the tips of holes drilled from the dam galleries. The hole made water for its full depth with large flows encountered at depths of 555, 610 and 680 feet. A seam of grout was encountered between depths of 630.5



* Exploratory Hole ~~#~~ 19/24.5 /25°

Runs 1 to 30

History of hole: Hole was core drilled to a depth of 702.2 ft. and was grouted in five stages. A total of 6,503 sacks of cement was injected.

Remarks: Good solid rock to 8'. Poor and broken rock to 107'.
Gradual increase in water to 107 ft.

*Drilled in 1943 during remedial grouting program by government forces

Figure 28

and 637.8 feet. Data on this hole was included in a letter report[15] dated May 24, 1943 and it is assumed that the hole was drilled in early 1943 after considerable supplemental grouting had been accomplished.

If some of the conditions found in the grouting programs and in the explorations with the additional grouting had been uncovered by a more comprehensive exploratory program in the preconstruction stage, the designers may have been influenced to plan a deeper and more conservative grout curtain.

38. Grout takes as related to geology. Detailed logs were not available for the exploratory holes. Descriptive material was presented on several holes in the report on additional grouting by Simonds and Boggess[6]. These data indicated that the grout takes were usually associated with broken zones or open seams as previously described for hole 108 in section 25. However, there were cases where the drill holes produced large water flows, but the grout takes were rather small.

VIII. RECOMMENDATIONS

39. Hoover Dam. The following recommendations are made for Hoover Dam:

(1) Continue to clean and maintain all drain holes.

(2) Check accuracy of all gages in the uplift measurement system and check response of all pipes.

(3) If uplift pressures have increased or do increase near the downstream toe, ream out and deepen the drain holes drilled from the powerhouse in 1938.

(4) For locating Phase II core holes to determine if grout has been eroded, select areas where known voids were encountered such as in A-138, D-98, D-1, D-22 and A-124.

40. Other large concrete dams. The following recommendations are made for the design and construction of other large concrete dams:

(1) Make a very comprehensive pre-construction geologic investigation including extensive explorations (core holes and drifts) to locate the defects in the rock that would affect the seepage and uplift.

(2) Design the grout curtain to bottom in rock of low permeability, where possible. The design should be based on a study of the geologic conditions and an assessment of the seepage flows and pressure patterns that will develop when the dam is completed and the reservoir is filled.

(3) Design the drainage system to intercept the voids in the rocks which would mean that the drain holes would be almost as

deep as the grout holes. Use multiple lines of drain holes for dams with a wide base width. Install drains in the abutments downstream to prevent instability due to seepage bypassing the grout curtain.

(4) Provide for additional core holes during installation of the grout holes and make appropriate changes in grouting and drainage programs.

(5) Establish maximum grouting and water-test pressures on the basis of effective weight and rock strength available at the point of application to resist the uplift. Include the effective uplift pressure of the grout in the line from the gage to the point of application.

(6) Establish initial water-cement ratios based on the takes in the water tests and thicken mixes based on grout takes.

(7) Insist on complete grouting of the holes as designed and continue split-spacing of closure holes if necessary to tighten the curtain. Do not leave gaps in the curtain by abandoning holes prior to refusal.

(8) Sound all completed grout holes with a heavy rod and top out hole with thick grout.

(9) Install uplift pipes at top of rock and also at depth in weak or broken seams that are critical to the stability of the dam.

APPENDIX

APPENDIX A

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APPENDIX B

DOCUMENTS REVIEWED (not listed in Appendix A)

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2. Nickell, F. A., Geology Reports on Hoover Dam, Nos. 1, 2, 10, 11 and 12, 1931-1932.

3. Specifications No. 519, Hoover Dam, Power Plant and Appurtenant Works, December 15, 1930.

4. SEED Evaluation Report for Hoover Dam, September 1980; prepared by Howard L. Boggs, Jack E. Allen and W. Harold Stuart, July 8, 1980.

5. Letter dated April 3, 1944, from W. H. Nader, Assistant Chief Designing Engineer, to Director of Power, Boulder City, Nevada, subject: "Supplemental foundation grouting - Boulder Dam".

6. Jones, Paul A., undated report entitled "High-Pressure Grouting - Foundation - Boulder Dam".

7. Memorandum dated April 21, 1939, from A. W. Simonds, Engineer, to Chief Designing Engineer, subject: "Grouting of Abutment Systems - Boulder Dam".

8. Letter dated July 13, 1948, from C. P. Christensen, Director of Power, Boulder City, Nevada, to Chief Engineer, Denver, Colorado, subject: "Drilling and grouting report - Arizona Spillway - Boulder Dam".

9. Field trip report dated May 15, 1946, by A. W. Simonds to Chief Engineer, subject: "Inspection of abutment grouting - Boulder Dam".

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APPENDIX C

HIGH PRESSURE GROUTING - FOUNDATION - BOULDER DAM

The drilling of grout holes in the foundation of the dam was done in accordance with Denver office drawing number 45-D-3138 except for a few minor changes.

The "A" Line holes were located as shown on the drawing but the maximum depth was limited to 150 feet instead of using the maximum depth of approximately 185 feet as given by the formula 0.22 h + 24', where h is the reservoir depth at the hole below elevation 1252.0. Pipe of 2½" diameter were placed for the "A" holes as indicated on the drawing.

The "B" line holes were located practically as shown except for a few additional holes which were located in the field to make the grouting of certain slips and faults more effective.

The "C" line holes were located practically as shown except that those shown located outside the heel of the dam were discontinued at elevation 750 with the idea in mind that if it was found necessary to do any more "C" line grouting the holes could be located and drilled to better advantage from the drainage gallery within the dam.

Before beginning the placing of concrete on the dam foundation it was necessary to construct drains to care for numerous small springs. All this spring water was led to 1½" Iron Pipe by direct connection with the spring, or by means of gravel finger drains, and the pipe were extended to the drainage gallery and the downstream face of the dam. At the time this work was done, short holes of approximately 30' depth were drilled which in effect were additional "B" holes. Pipe from the additional "B" holes were extended to the galleries and downstream face also. In all, there were about 200 of these pipe.

A grout system was laid out on each abutment with condulets spaced at approximately 10 foot centers for the purpose of grouting the joints between the concrete in the dam and the rock at the abutments after the reservoir is filled, and the deflection at the abutments has taken place.

Grouting was begun by grouting all the "B" holes as shown on the drawing with the additional holes which were loc-

ated for more effective grouting of certain open seams and crevices. This work was all done before any concrete was placed on the area covered by those holes, and was done at comparatively low pressures of from 100# to 150# per square inch, and for the purpose of solidification of the surface rock, so that a greater penetration and more effective sealing of the fine rock seams could be secured by the high pressure grouting of the "A" line and "C" line holes.

The first high pressure grouting done on either "A" or "C" holes was done on eleven "A" holes at the lowest elevation. Alternate holes were drilled and all eleven holes were hooked up in a battery and grouting was begun on a hole at the end of the line of eleven holes - and as leaks occured from one hole to another, pumping was begun on the hole in which the leak occurred, alternating the pumping between holes at a few minute intervals. These holes were tried out with grout of 3.0/1.0 and 2.0/1.0 water cement ratios and pressures of 1000# per square inch, with very little success as will be shown later.

After the first eleven "A" had been grouted, it was found advisable to begin grouting the "C" line holes in order to get this work out of the way before starting the storing of water. The original scheme called for grouting the "A" line before grouting the "C" line and results obtained while grouting some of the first "C" line holes were to determine the spacing of holes, and extent of the "C" line. With the change in schedule in mind it was then decided to grout the "C" line holes on the 600' elevation or bench end then core drill three "A" line holes on the 600 foot elev. bench on each side of the canyon and determine from this core drilling the extent of the "C" line and spacing of holes on the same line.

The core drilling was completed and no indication of grout was found in any of these holes, and the character of the rock indicated very tight seams with very few water courses.

Grouting of the "C" line holes was resumed and completed to elevation 750 as shown on the drawing, at pressures ranging from 500# to 800# per square inch, and at the same time grouting of the "A" line holes was resumed with the understanding that an "A" hole and a "C" hole could not be grouted on the same side of the canyon at the same time.

The grouting of the "C" line holes was done progressively, i.e. a hole was drilled and grouted before the succeeding hole was drilled. In order to speed up operations and grouting of "A" line holes the successive grouting method was not strictly enforced. The contractor was allowed to drill any number of holes without loss of hole if the travel of grout from one hole to another drilled hole passed a hole that had already been grouted - when conditions of this kind did occur, both holes were connected to the grout pump and grouting continued intermittently on each hole at intervals of 10 minutes

to 15 minutes. Pressures of approximately 1000# per square inch were used to elevation 700, with a decrease in pressure of 100# for each 100 feet in elevation.

The grouting of drains and additional "B" holes was handled in the same manner as the "A" holes, using pressures of 1000# per sq.in. for the area covered by the upstream 8 blocks, the area covered by blocks 9 to 13 inclusive was grouted at 750# per sq.in. and the balance of the area covering approximately the downstream ¼ was grouted at a pumping pressure not to exceed 500# per sq.in. This grouting was begun after the "A" line grouting had been completed, and was carried on intermittently in order to coordinate this work with other grouting and allow the contractor to work his crew to best advantage.

In beginning the grouting on any job, the maximum water cement ratios and pressure, must be determined to correspond with the effectiveness which is considered necessary. Since pressures of 1000# per sq.in. was considered necessary then it must be considered that a relatively thin mixture must also be used in order to penetrate the finer seams. After the first eleven "A" holes had been grouted with w/c ratios of 2.0/1.0 and 3.0/1.0, the procedure for grouting was about as follows with slight variations.

All grouting was done with a Gardner Denver Duplex Steam pump reconstructed with hard rubber valves and pistons for pumping grout. Gauges were placed on the air line and where the grout line was more than 100' from the pump to hole, one gauge was placed on the grout line at the pump and another at the hole, and payment for pressure was allowed relative to gauge at the hole, for pumping pressures above and below 500#; this being necessary for the reason that the original specifications required 500# as a maximum pressure and it was later decided to use pressure up to 1000# and the contractor was allowed extra compensation for the increased pressure.

In order to feel out a hole where there are three variables with which to contend, namely, w/c ratios, pump speed, and pressure, a constant must be assumed. Since it is impossible before starting a hole to assume a pressure or w/c ratio which would be consistent for the bulk of grouting, then a pump speed must be assumed and a w/c ratio large enough that there will be no danger of plugging the hole*. In conformity with this method, each hole was started with 7.0/1.0 water cement ratio, with pump throttled down until it was pumping very slowly. If the hole showed pressure of 500# or more, the water cement ratio was not changed until it was seen what effect the gradual increase of pump speed would have on the pressure. If when the pump had reached a normal pumping speed of approximately 15 forward strokes per minute on each piston, the hole seemed to loosen up or showed no increase in pressure, then the water cement ratio was decreased to 5.0/1.0 and so on. When a

hole was found that the water cement ratio could be decreased to 1.0/1.0 or 0.75/1.0, which was seldom the case, the pump was then speeded up to fill the open territory as quickly as possible, and when pressure was being reached the w/c was increased in order that fine seams that had not already been sealed off might still be grouted.

Occasionally holes were found, where the water cement ratio could be decreased gradually from 7.0/1.0 to 3.0/1.0 with but slight effect upon the pressure or pumping speed, but this was not the rule as generally a decrease in water cement ratio resulted in a corresponding increase in pressure. Very close watch was kept of the gauges, as an index to the results being obtained, and water cement ratio and pump speed controlled or corrected to meet the condition.

It was not uncommon for grout to show in construction joints in the dam, in which cases the grout was thickened as quickly as possible to seal off the leak at pressures varying from about 500# per sq.in. near the base of dam to about 300# per sq.in. above elevation 1100.

The results obtained in general were very satisfactory after the first 11 "A" holes had been grouted. The penetration by starting a hole with thin grout was very well illustrated when 182 sacks of cement were forced into 8 intermediate holes to the 9 holes previously mentioned, which took only 18 sacks of cement.

The average amount of grout per hole increased materially as the grouting proceeded from the base toward the top of abutments. This increase would no doubt have been greater if it were not for the fact that leaks into the abutment grouting system caused the abandoning of "A" line holes before entirely completed in order to prevent the clogging of the abutment system. Water was kept flowing thru the abutment system at all times during the grouting of the "A" line, and when a leak into the system occurred, the grout was thickened rapidly to 1.0/1.0 w/c ratio in order to seal the leak and if the leak could not be sealed with thick grout, the "A" hole was abandoned and the abutment system was flushed until clear water in the return flow was maintained. Much more satisfactory results could be obtained if two systems could be designed for future work so that the abutment could be grouted thru one system before doing the curtain grouting and then after the reservoir is filled, grout thru the other system to take care of any opening dur to deflection.

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*A suggested standard for w/c for starting any hole, would be to use a w/c with w = one unit for each 100# of ultimate pressure, i.e. 5.0/1.0 w/c for 500# pressure and 10.0/1.0 w/c for 1000# pressure.

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Chief Inspector

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